TECHNICAL SESSION PROCEEDINGS

Irrigation Show 2013
Education Conference

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Pressure Regulating Valve Characteristics

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Abstract. *The Cal Poly ITRC tested performance characteristics of pressure regulating valves from a variety of manufacturers. The purpose of the testing was to evaluate the ability of different models of valves to regulate the pressure in a low-pressure system. The testing concentrated on three specific valve performance characteristics: minimal variance from the target downstream pressure caused by changes in flow rate or inlet pressure; minimal hysteresis in outlet pressures; and minimal pressure loss (at low inlet pressures) across the valve. The testing indicated that valves with 2-way pilots are not suited for truly low pressure systems due to an inherently higher pressure differential. However, most of the comparable valves with 3-way pilots have the ability to maintain an outlet pressure of +/- 1.5 psi.*

Keywords. Pressure regulating valve, microsprayer, pressure compensation, irrigation, drip irrigation, micro irrigation

Introduction

Agricultural irrigation systems, especially drip and microirrigation systems, require constant pressures in order to avoid variations in application rates or pipe breaks due to sudden pressure surges (called "water hammer"). Therefore, in areas where pressure drops or surges are common, pipelines to the irrigation system often require pressure regulating valves at the heads of submains or manifolds.

Pressure regulating (PR) valves have a two-fold purpose for agricultural irrigation: they must be able to maintain a pre-set maximum operating pressure in the water line downstream of themselves, and they also serve as isolation valves that can be used to turn an irrigation system or block on and off. Since all pressure regulating valves currently on the market can successfully provide on/off control, the testing conducted by ITRC focused solely on measuring the performance of the valves' pressure regulation.

An "ideal" PR valve should provide sufficient performance in the following areas:

- *Minimal variance from the target downstream pressure caused by changes in flow rate or inlet pressure*. In other words, regardless of increases in the pressure or flow rate upstream of the valve (the valve's "inlet pressure"), the valve must be able to maintain the maximum pressure in the downstream pipeline (the valve's "outlet pressure").
- *Minimal hysteresis in outlet pressures caused by cyclical (on/off) operation as exhibited between irrigation events*. Irrigation systems undergo frequent pressure changes due to blocks or systems turning on and off, backflushing filters, plugged emitters, or other reasons. The pressure regulating valve must be able to respond quickly to changing flow rates and pressures with minimal variations in performance.
- *Minimal pressure loss (at low inlet pressures) across the valve to enable low pump outlet pressures*. All pressure regulating valves require an inlet pressure that is larger than the

target outlet pressure. The "pressure loss across the valve" is the difference between the target outlet pressure and the minimum inlet pressure required to produce a constant outlet pressure. In an ideal PR valve, the loss would be minimal, meaning that the valve would not require much excess inlet pressure in order to maintain a low outlet pressure.

Tests

ITRC created three separate tests to measure the performance characteristics of each pressure regulating valve based upon the points above. The three tests were designed to determine the following characteristics:

(1) The ability of pressure regulating valves to maintain a constant outlet pressure, with changes in upstream inlet pressures.
(2) The ability of pressure regulating valves to maintain a constant outlet pressure, with changes in flow rates.
(3) The minimum inlet pressure required to regulate an outlet pressure of 13 psi at various flow rates

Valve Assortment

The valves tested by ITRC were provided by manufacturers, distributors and irrigation dealers specifically for this project. Product representatives and dealers were given a specific description regarding the constraints of the testing and the expected abilities of the valves to perform at low inlet and outlet pressures. A variety of valve configurations and sizes were received by ITRC for testing that produced a range of results, sometimes directly related to the valve size or configuration.

ITRC used all valves received in Test 1. During the test, two issues became apparent:

- Pressure regulating valves are commonly controlled by either a 2-way pilot or a 3-way pilot. Due to the design characteristics of the 2-way pilot valves, none of the 2-way pilot valves were able to perform within the requirements of a true low pressure system application, but instead all required a substantial pressure loss across the valve body to enable downstream pressure regulation. Therefore, it was determined that ***two-way pilot valves are not suited to low-pressure system applications*.**
- Multiple valves were received by ITRC with incorrect hardware combinations such as pilot springs and diaphragms, which negatively affected the performance of the valves. ITRC was able to identify certain elements that made these valve combinations unsuitable for low-pressure system applications.

As a result of the two discoveries mentioned above, only ***correctly-equipped 3-way pilot valves*** were used for Tests 2 and 3.

Test Results

Test 1: Performance with Changing Inlet Pressures

The intention of the first test was to start testing the valves at an inlet pressure above a low pressure system target level (13 psi), and then slowly decrease the inlet pressure until the inlet pressure reached 10 psi, forcing the valve to fully open in order to attempt to regulate the outlet pressure. Then, the flow was slowly increased until it reached the original test starting pressure. After the initial pilot adjustments, the pilot setting was not adjusted throughout the test.

As seen in Figure 2, the graphs provided were intended to show two lines: The blue line represents the valve's outlet pressure in relation to the inlet pressure as the inlet pressure decreases. The red line represents the outlet pressure as the inlet pressure increases back to the test's starting pressure. A "good" valve performance would look something like the graph in Figure 2, where the valve is able to maintain the target pressure relatively well until the inlet pressure drops to slightly above to the target outlet pressure, and the valve can no longer regulate. Then, a well-performing valve should be able to repeat the same relationship in reverse, as the pressure increases again (i.e., with minimal *hysteresis*).

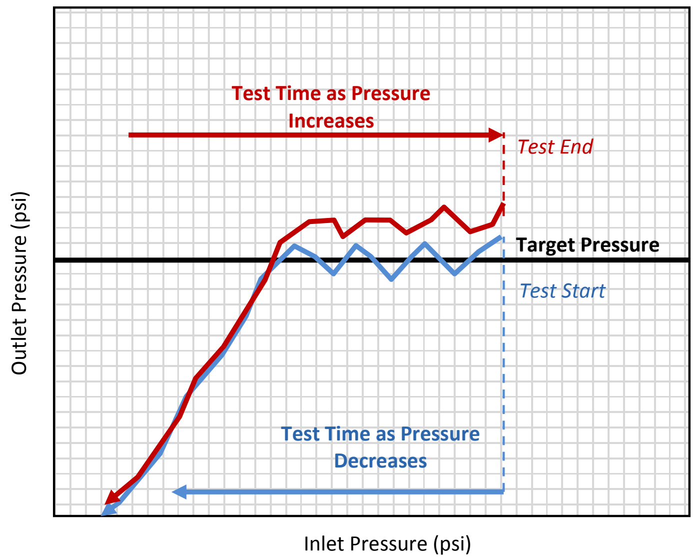

Figure 1. Example Test 1 graph

Pressure Regulating Valves with 2-Way Pilots

ITRC was supplied with PR valves that were plumbed with 2-way pilots. As shown in the following graphs, none of the 2-way pilot valves were able to perform satisfactorily during Test 1, because all of the models required inlet pressures that were significantly higher than the "low-pressure" test scenario of a 13 psi target outlet pressure.

Two-way pilot PR valves are much better suited for situations where the inlet pressure is substantially higher than the target outlet pressure. However, since this set of tests was focused on low-inlet pressure applications, testing on these models was halted after the first half of Test 1, and none of the valves with 2-way pilots were included in Tests 2 and 3. Therefore, the graphs for the 2-way pilot designs only show the results of the decreasing-pressure part of Test 1.

Table 1 lists the 2-way pilot models and their performance graphs are included in Figure 2.

Table 1. List of pressure regulating valve models with 2-way pilot designs used in Test 1

Manufacturer	Model	Size (in.)	Pilot Type	Pilot Model	Spring Model	Spring P Range (psi)	Diaphragm Type
Bermad	IR-120	4	2-way	PC-20	K	7 to 45	Standard
Bermad	IR-120	6	2-way	PC-20	K	7 to 45	Standard
John Deere	V2000	3	2-way/3-way hybrid	T	Standard	7 to 44	Standard

Ooval	PH3N00G001	3	2-way	P-21	Blue	7 to 144	Standard
Ooval	PH0400G001	4	2-way	P-21	Red	7 to 220	Standard
Ooval	ZH3NRDTWO2	3	2-way	P-21	Blue	7-145	Standard
Ooval	ZH3NRDTWO2	3	2-way	P-21	Red	7 to 220	Standard
Ooval	ZH04RDG001	4	2-way	P-21	Red	7 to 220	Standard

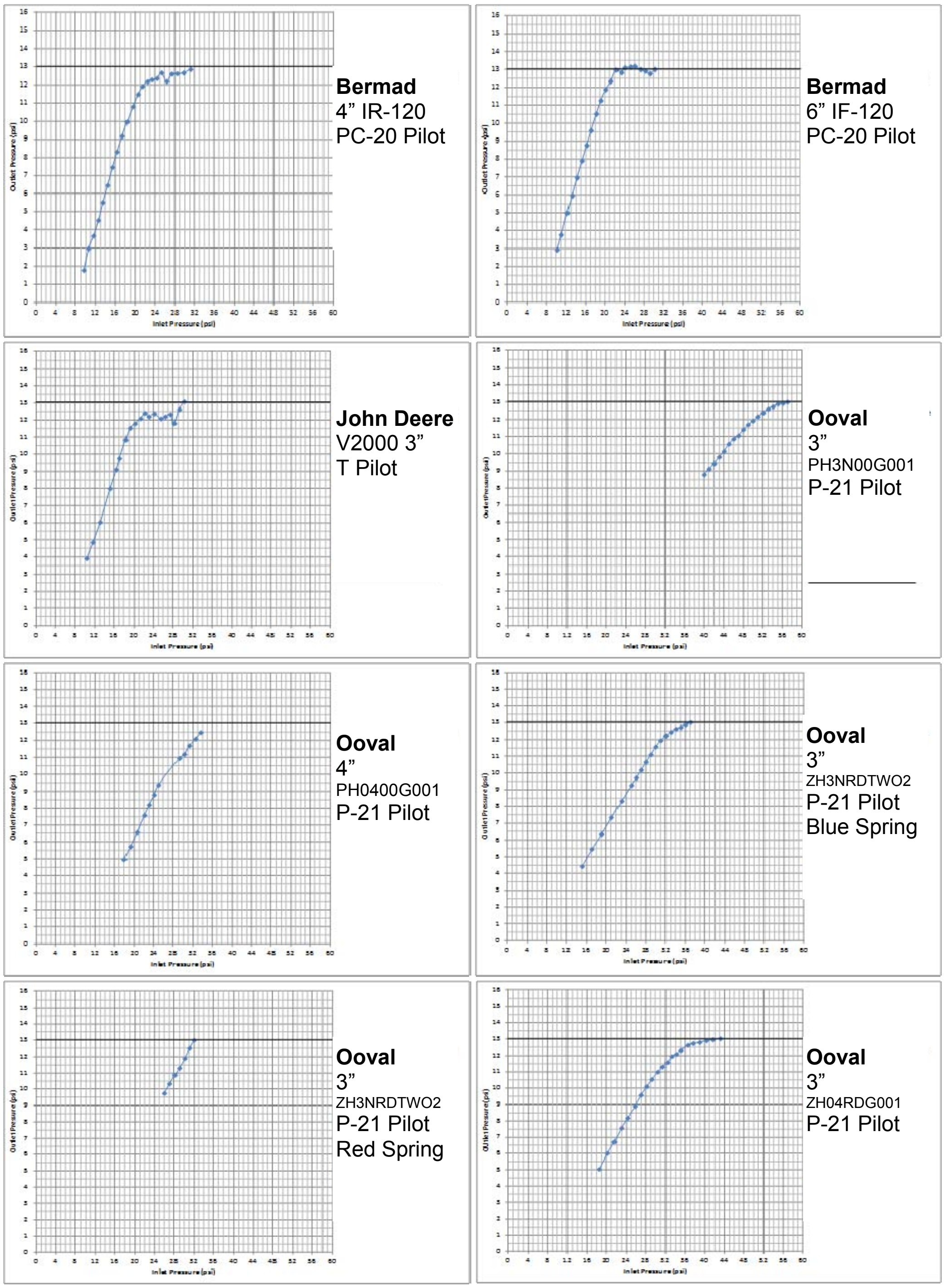

Figure 2. Pressure regulating valve models with 2-way pilot designs used in Test 1

Pressure Regulating Valves with Incorrect Configurations

Four of the PR valves received showed erratic results during Test 1. Upon further inspection, it was apparent that all four had arrived with the incorrect hardware for the testing configurations: three contained diaphragms for high inlet pressure applications, and one had a high-pressure pilot spring. Therefore, these four valves were not used for Tests 2 and 3.

Table 2 lists the low-performing valves used in Test 1, and their performance graphs are shown in Figure 3.

Table 2. List of pressure regulating valve models with incorrect hardware used in Test 1

Manufacturer	Model	Size (in.)	Pilot Type	Pilot Model	Spring Model	Spring P Range (psi)	Diaphragm Type	Hardware Issue
Dorot	Series 100	3	3-way	29-100	Yellow	7 to 30	032 (HP)	HP Diaphragm
Dorot	Series 100	4	3-way	29-100	Yellow	7 to 30	032 (HP)	HP Diaphragm
Dorot	Series 100	4	3-way	29-100	Yellow	7 to 44	032 (HP)	HP Diaphragm
Ooval	ZH04RDG001	3	3-way	P-31	Red	8-88	Standard	HP Pilot Spring

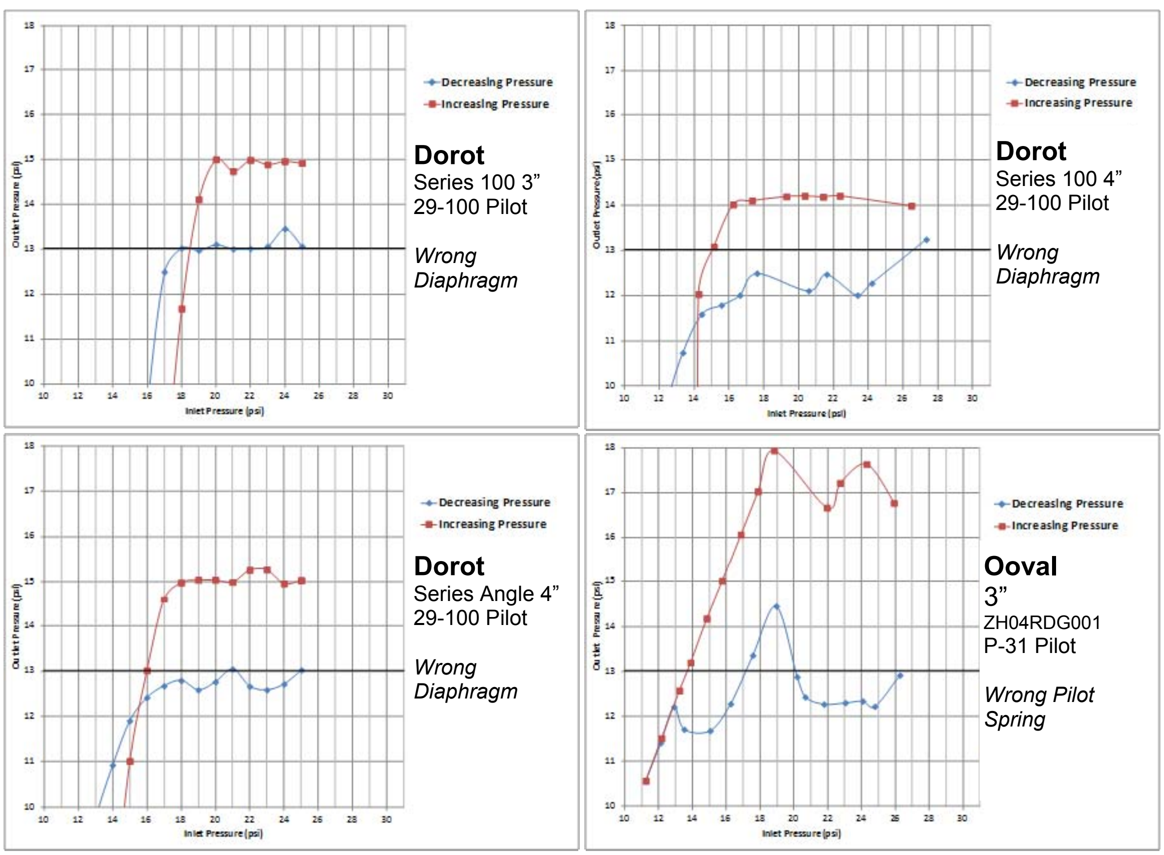

Figure 3. Pressure regulating valve models with incorrect hardware used in Test 1

Pressure Regulating Valves with 3-Way Pilots and Correct Design

Fourteen of the pressure regulating valves provided to ITRC for testing contained 3-way pilots and the appropriate design for the low inlet pressure test scenarios (see Table 3). Three of the valves performed poorly despite having the correct hardware, and were not carried forward to Test 2 and Test 3. Performance graphs for these valves are included in Figure 4 through Figure 5.

Table 3. List of appropriate valves used in Test 1

Valve ID	Manufacturer	Distributor	Model	Size	Pilot Type	Pilot Model	Spring Model	Spring P Range (psi)	Diaphragm Type
5-A*	Bermad	Bermad	IR-120	6	3-way	PC-X	K	7 to 45	Standard
4-A	Bermad	Bermad	IR-120	4	3-way	PC-X-A-P	K	7 to 45	Standard
4-B	Dorot	Netafim	Series 96	4	3-way	29-100	Yellow	7 to 30	095 (HP)
4-C*	Dorot	Netafim	Series 96	4	3-way	31-310	Yellow	7 to 30	095 (HP)
4-D	Dorot	Netafim	Series 96	4	3-way	31-310	Yellow	7 to 30	179 (LP)
4-E	Dorot	Netafim	100	4	3-way	29-100	Yellow	7 to 30	005 (LP)
4-F	Nelson	Nelson	800	4	3-way	Standard	Standard	5 to 50	Standard
4-G	Ooval	Eurodrip	PH0400G001	4	3-way	P-31	Blue	5 to 36	Standard
4-H	Ooval	Eurodrip	ZA04RDA001L	4	3-way	P-31	Blue	5 to 36	Standard
4-I	Rafael	Jain	RAF-P	4	3-way	PC	Blue	7 to 22	Standard
3-A	Bermad	Bermad	DN80	3	3-way	PC-X-A-P	K	7 to 45	Standard
3-B	Dorot	Netafim	Super Gal	3	3-way	29-100	Yellow	7 to 30	Standard
3-C	Ooval	EuroDrip	ZH3NRDG001	3	3-way	P-31	Blue	5 to 36	Standard
3-D	Rafael	Jain	RAF-P	3	3-way	PC	Blue	7 to 22	Standard

*Three valves tested did not perform well during Test 1; therefore, these valves were not tested further

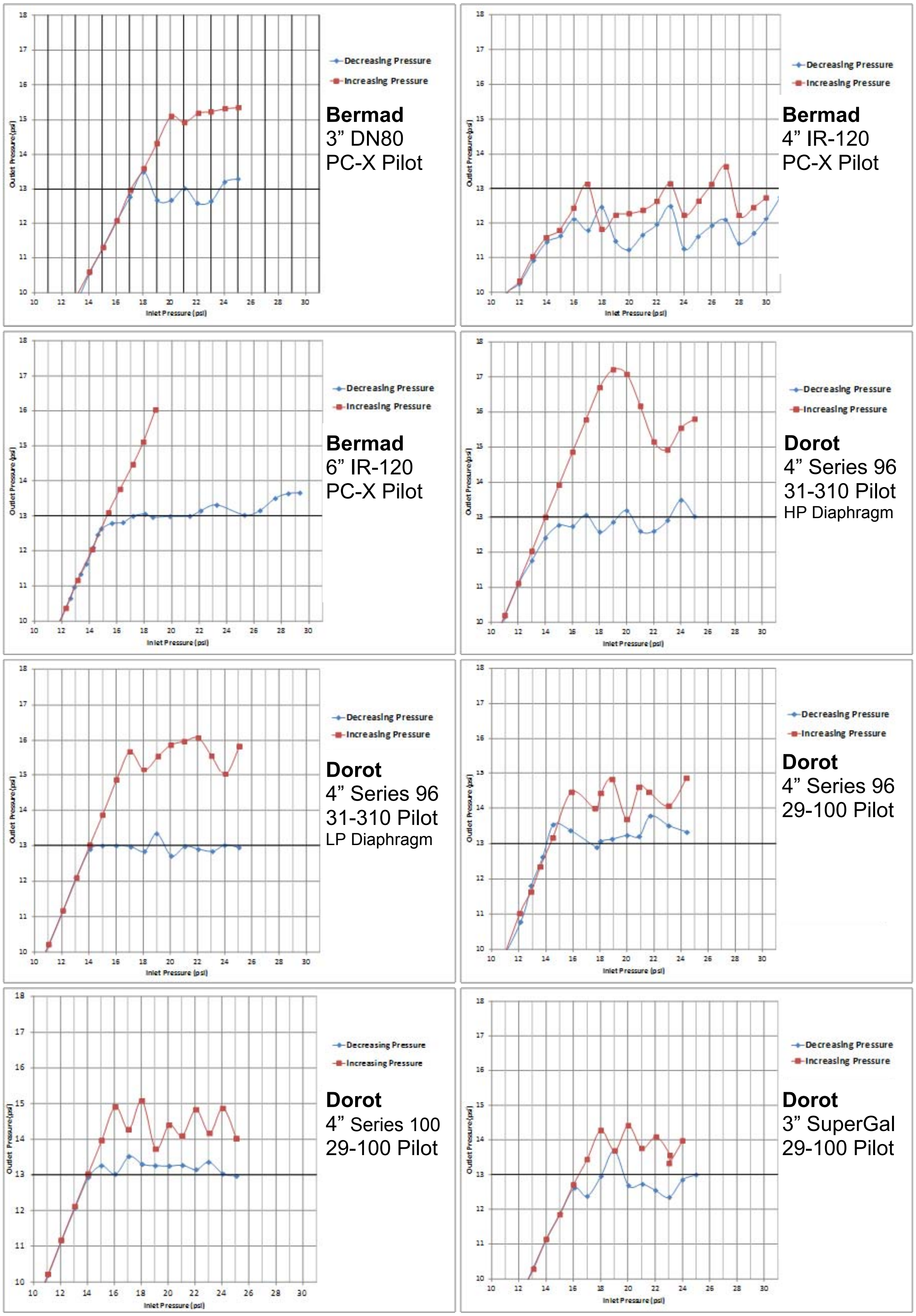

Figure 4. Appropriately configured valves used in Test 1

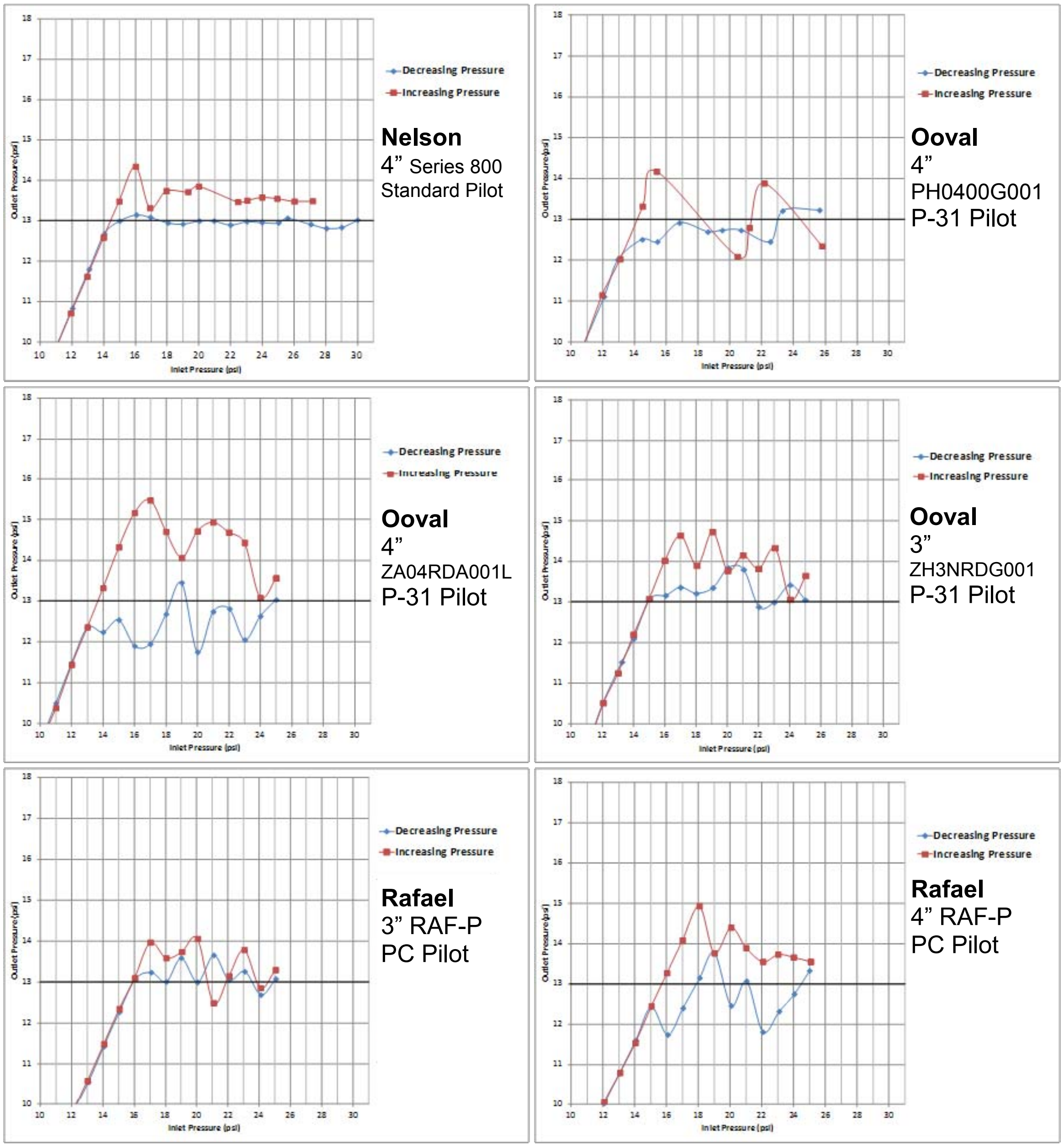

Figure 5. Appropriately configured valves used in Test 1 (continued)

Test 2: Performance with Changing Inlet Flow Rates

The intention of the second test was to configure the valve inlet and discharge pressures at conditions replicating a low pressure system at a low flow rate of 100 GPM. The test proceeded by substantially increasing the flow rate to 500 GPM while maintaining the initial inlet pressure and monitoring the subsequent outlet pressure. Due to large pressure losses with some valves, a flow rate of 500 GPM was not reached. After the initial pilot adjustment, the pilot setting was not changed throughout the test.

As seen in Figure 6, the graphs provided were intended to show two lines: The blue line represents the valve's outlet pressure in relation to the flow rate through the valve. The red line represents the inlet pressure in relation to the flow rate, which remained constant throughout the test. An “ideal” valve performance would show nearly parallel lines, meaning the valve was able to maintain the target pressure relatively well throughout a large range of flow rates.

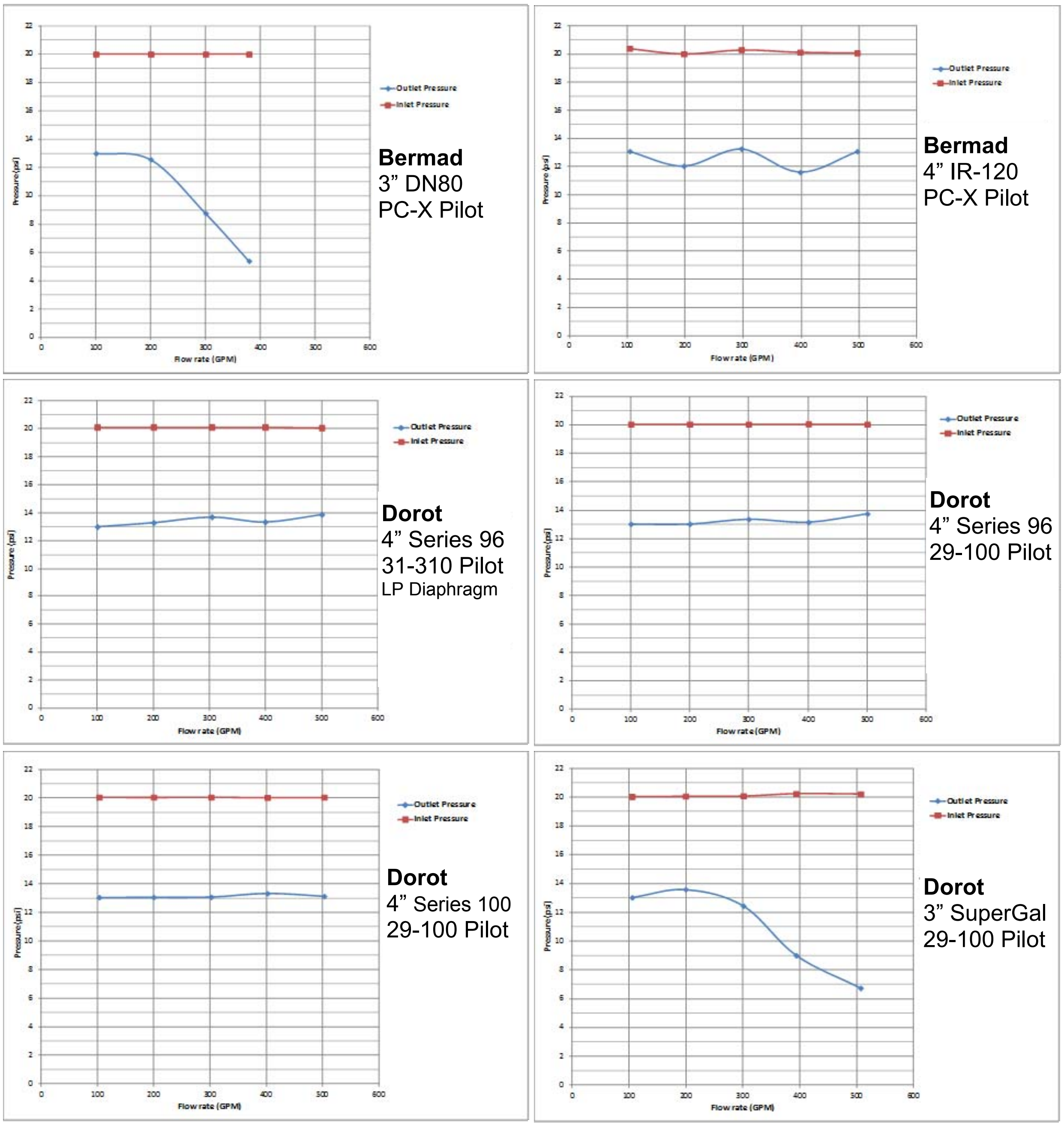

Figure 6. Test 2 results

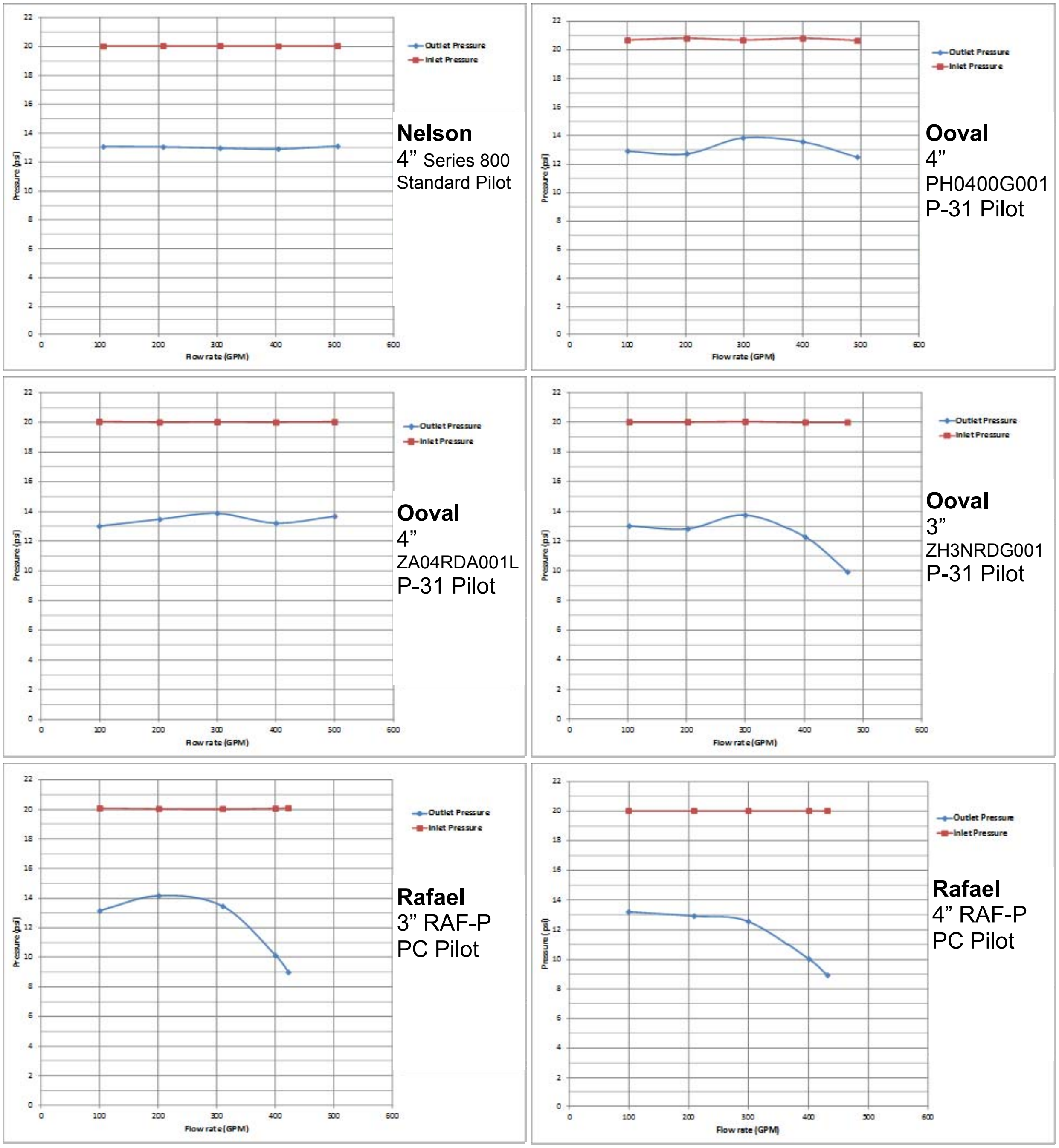

Figure 7. Test 2 results (continued)

Test 3: Minimum Valve Pressure Loss at Various Flow Rates

Test 3 examined the minimum valve pressure loss at various flow rates. This was determined by subtracting the downstream pressure at each measured flow rate from the minimum upstream pressure that still maintained the target downstream pressure. The results of the ITRC testing were then compared with the values for minimum valve pressure loss listed for each model in the manufacturers' published specifications, as well as the values provided by the equipment distributor (if available).

The overall results are presented graphically in Figure 8 and in table format in Table 4. The test vs. manufacturer value graphs are presented for each model individually in Figure 9 through Figure 10.

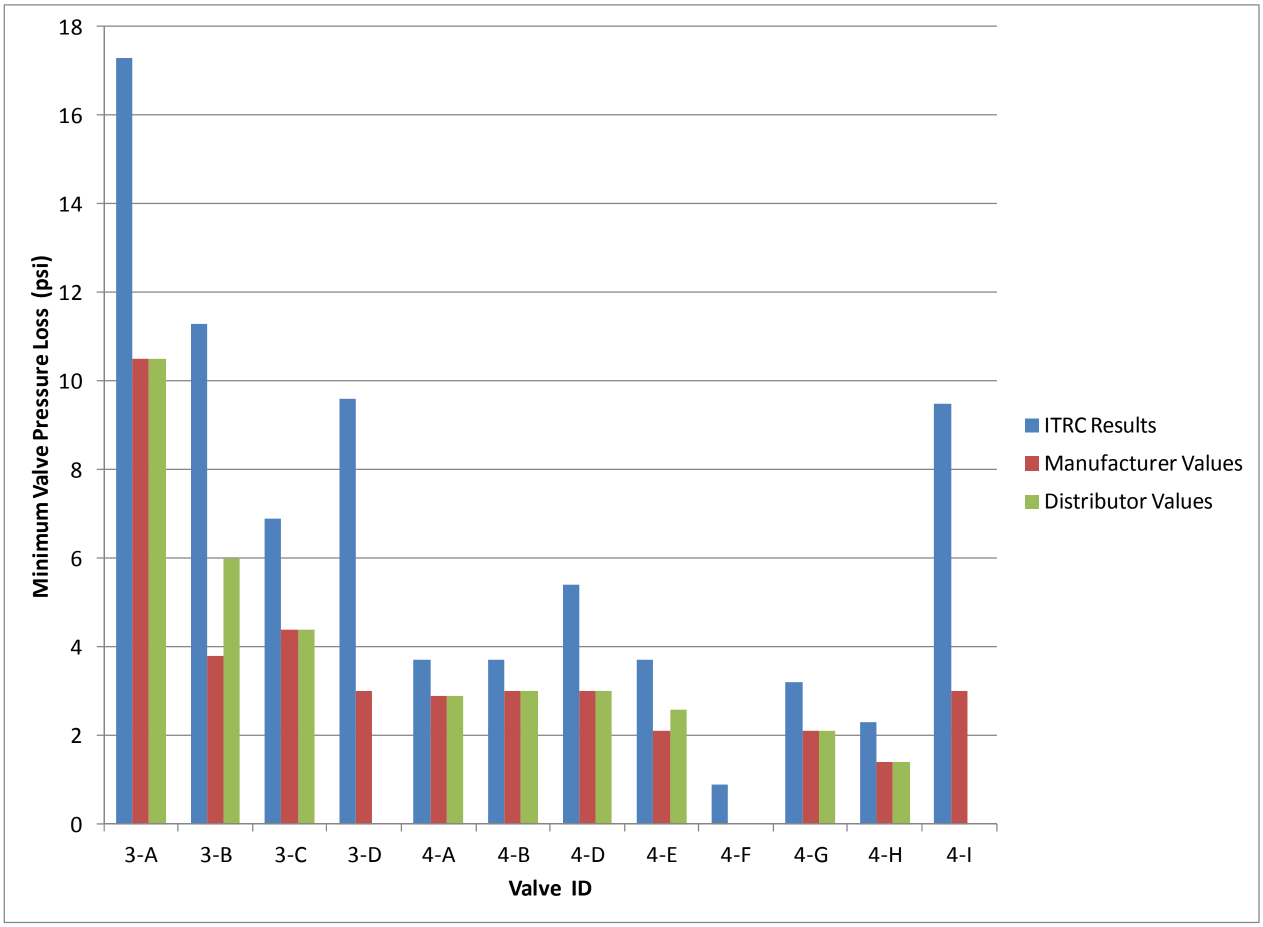

Figure 8. Minimum valve pressure loss (during operation by pilot control) at 13 psi outlet pressure at 400 GPM

Table 4. Minimum valve pressure loss (during operation by pilot control) at 13 psi outlet pressure at 400 GPM

										Minimum Valve Pressure Loss (During Operation by Pilot Control) to Outlet 13 PSI @ 400 GPM		
Valve ID	Manufacturer	Distributor	Model	Size	Pilot Type	Pilot Model	Spring Model	Spring P Range (psi)	Diaphragm Type	ITRC Measured Value (psi)	Manufacturer Stated Value (psi)	Distributor Stated Value (psi)
4-A	Bermad	Bermad	IR-120	4	3-way	PC-X-A-P	K	7 to 45	Standard	3.7	2.9	2.9
4-B	Dorot	Netafim	Series 96	4	3-way	29-100	Yellow	7 to 30	095 (HP)	3.7	3	3
4-D	Dorot	Netafim	Series 96	4	3-way	31-310	Yellow	7 to 30	179 (LP)	5.4	3	3
4-E	Dorot	Netafim	100	4	3-way	29-100	Yellow	7 to 30	005 (LP)	3.7	2.1	2.6
4-F*	Nelson	Nelson	800	4	3-way	Standard	Standard	5 to 50	Standard	0.9		
4-G	Ooval	Eurodrip	PH0400G001	4	3-way	P-31	Blue	5 to 36	Standard	3.2	2.1	2.1
4-H	Ooval	Eurodrip	ZA04RDA001L	4	3-way	P-31	Blue	5 to 36	Standard	2.3	1.4	1.4
4-I*	Rafael	Jain	RAF-P	4	3-way	PC	Blue	7 to 22	Standard	9.5	3	
3-A**	Bermad	Bermad	DN80	3	3-way	PC-X-A-P	K	7 to 45	Standard	17.3	10.5	10.5
3-B**	Dorot	Netafim	Super Gal	3	3-way	29-100	Yellow	7 to 30	Standard	11.3	3.8	6
3-C**	Ooval	EuroDrip	ZH3NRDG001	3	3-way	P-31	Blue	5 to 36	Standard	6.9	4.4	4.4
3-D*	Rafael	Jain	RAF-P	3	3-way	PC	Blue	7 to 22	Standard	9.6	3	

* No pressure loss information available
** ITRC value was extrapolated; best estimate for manufacturer stated value

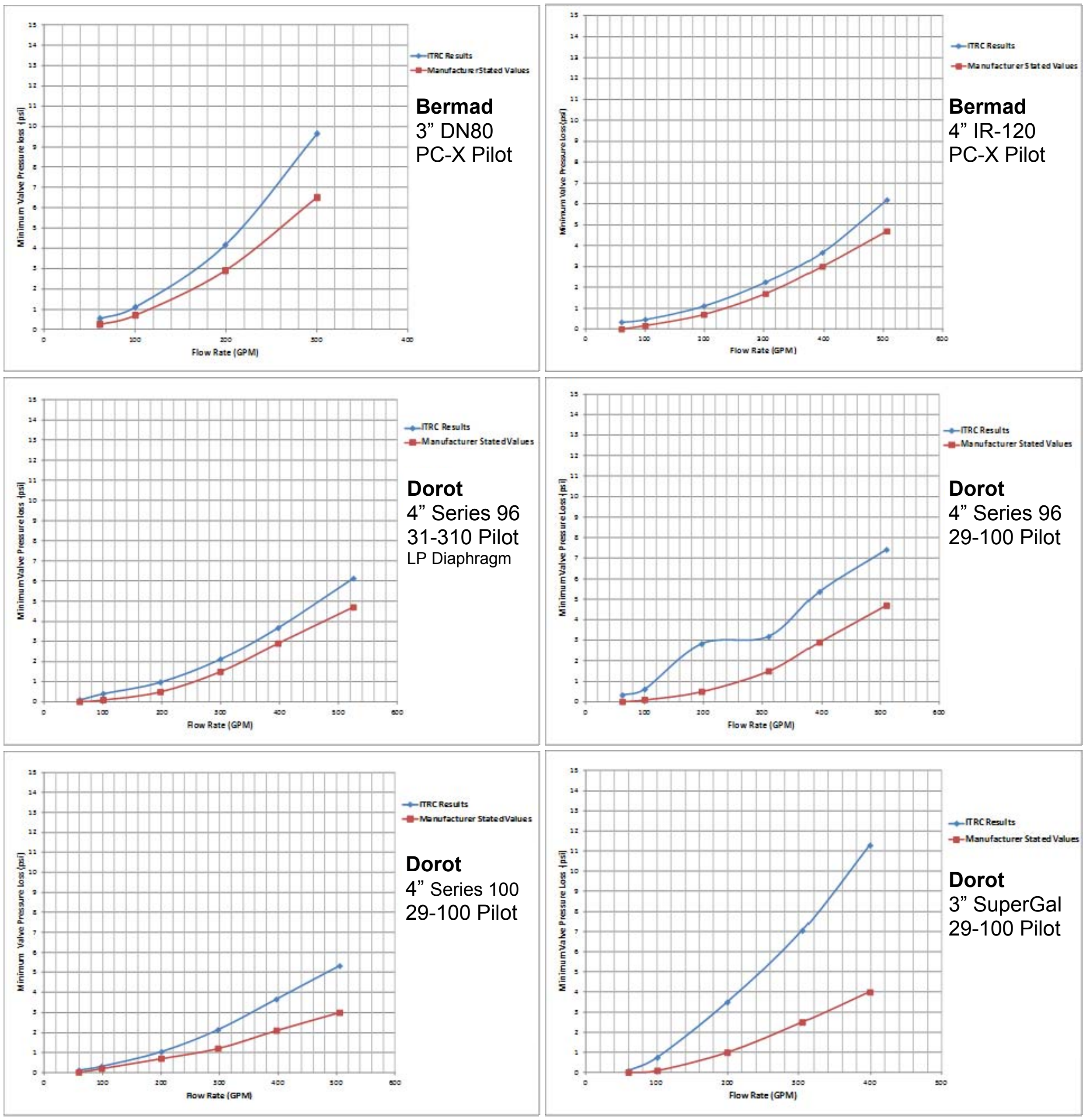

Figure 9. Test 3 results

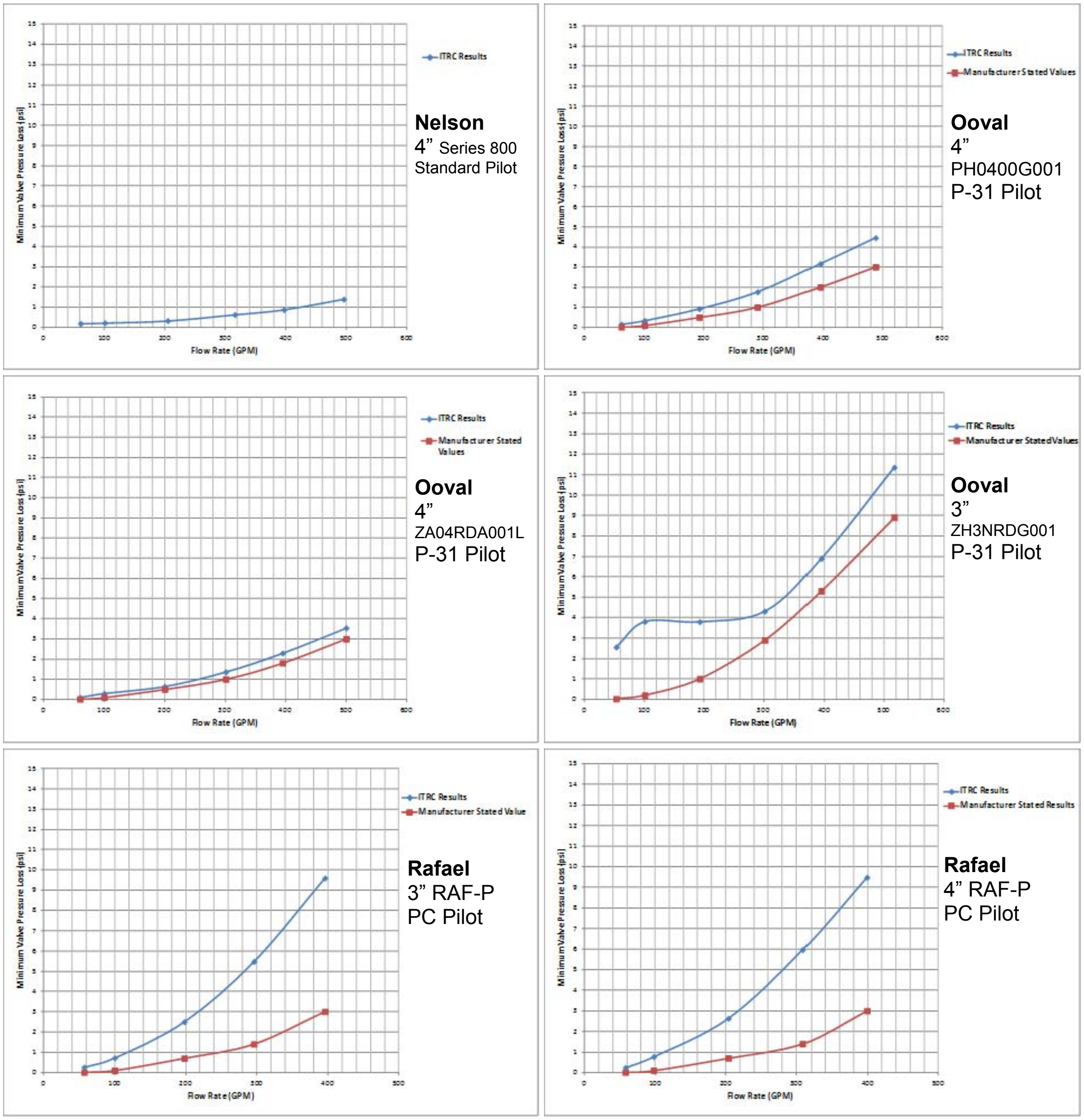

Figure 10. Test 3 results (continued)

Conclusion

The test results indicate the following conclusions:

1. Pressure regulating valves with 2-way pilots are not suited for low truly low pressure systems due to an inherently higher pressure differential requirement. In other words, if they valves with 2-way pilots are adjusted to regulate an outlet pressure of 13 psi, the majority of valves tested required an inlet pressure of over 20 psi to function.

2. All of the comparable valves with 3-way pilots were affected by the following performance characteristics:
    a. *Regulated outlet pressure consistency.* Within a specific operating range, the majority of valves with 3-way pilots have the ability to maintain an outlet pressure of +/- 1.5 psi. Only one valve was able to maintain an outlet pressure within +/- 0.5 psi.
    b. *Hysteresis.* All of the valves with 3-way pilots operated differently during decreasing inlet pressures compared to increasing inlet pressure conditions. Some valves exhibited as much as a 2 psi difference in regulated outlet pressures due to hysteresis.
3. Many of the valves received by ITRC had incorrect diaphragms or pilot springs installed despite extensive specification of performance requirements. It is therefore critical that end users supply specific performance requirements to irrigation dealers and perhaps verify the configuration before installation.

Acknowledgements
ITRC would like to acknowledge the following valve manufacturers for cooperation during the testing: Eurodrip USA, Jain Irrigation, John Deere Water Technologies, Nelson Irrigation, and Netafim.

Pressure Compensating Emitter Characteristics

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Abstract. *If a PC (pressure compensating) emitter can "lock in" to its design flow at a low pressure, the overall pressure requirement into a hose can be reduced. Twenty-eight (28) common PC emitter and PC microsprayer models from a range of manufacturers were tested to determine the minimum operating pressures, as well as the factors that impact uniformity (coefficient of variation at various pressures, and how steady the flows remain at various pressures). Implications on energy consumption are discussed. Many of the low flow PC emitters had remarkably constant flow rates above some minimum compensating inlet pressure (MCIP), although microsprayers tended to have poorer performances. Some PC emitters do not deliver the average flow rate that is advertised.*

Keywords. Pressure compensating emitter, microsprayer, pressure compensation, irrigation, drip irrigation, micro irrigation

Introduction

The Irrigation Training & Research Center (ITRC) of California Polytechnic State University San Luis Obispo (Cal Poly) tested 28 different pressure-compensating (PC) models of drip/micro irrigation emission devices from a total of nine manufacturers in order to compare independent laboratory testing with manufacturer specifications.

Pressure compensating (PC) emitters are marketed as having the ability to regulate flow rates despite variations in inlet pressures. The pressure-compensating component of the emitter involves an elastic diaphragm that enlarges or contracts an orifice open area in relation to inlet pressures to provide a more consistent flow rate. PC emitters are typically used more frequently in orchards than with other crops because they are generally installed with long lengths of above-ground hose that can be used on terrain with variations in elevation.

Because the act of pressure compensation requires water pressure to manipulate the elastic diaphragm, there exists a minimum compensating inlet pressure (MCIP) for every emitter. Many manufacturers publish discharge graphs that show the relationship between inlet pressure and emitted flow rates, where inlet pressures within a specified range above the MCIP produce a nominal flow rate.

This paper focuses on three aspects of PC emitter performance:

- Average emitter flow rate
  - The expected flow rate of each irrigation set or "block" directly affects the design of other major system components including the pump, filters, pipe sizes, control valves, etc.
  - Differences between the actual and expected average emitter flow rate can have substantial effects on irrigation scheduling and in-field irrigation uniformity, subsequently affecting crop yields and revenue.
- Manufacturing coefficient of variation (cv)
  - The variation of individual emitter flow rates due to manufacturing tolerances is a critical characteristic used during the selection of the emitter product.
  - Differences between the actual and expected "cv" of newly installed systems will affect the irrigation uniformity.
- Minimum compensating inlet pressure (MCIP)
  - The MCIP is important when the design attempts to minimize system energy consumption by lowering pump discharge pressures.
  - Differences between the actual and expected minimum inlet pressure will directly affect irrigation uniformity if the MCIP is not supplied at lower pressure areas in the field (i.e., the ends of hoses, furthest laterals, highest elevations).

An "ideal" emitter for use in a low pressure irrigation system should provide sufficient performance in the following areas:

- Minimal variance from the nominal flow rate throughout the specified operating pressure range
- Minimal variance in flow rate due to manufacturing variations
- Minimal pressure required to emit the nominal flow rate

Testing

The testing of pressure compensating emitters is sometimes performed only after the samples are flushed with clean water to wash the elastic diaphragm of a talc powder used during the manufacturing process. All of the models tested were first flushed and "conditioned" under pressure for a minimum of 18 hours. Discussions with manufacturers led to an increase in the flushing and "conditioning" duration to a minimum of 48 hours. The majority of models were retested after being flushed for an additional 48 hour period. Table 1 lists the conditioning times for each emitter model. The flushing time had no significant influence on the test results. Where applicable, the results from testing after flushing for 48 hours are provided. Detailed testing protocol, including a description of equipment used, can be found in a more detailed report on ITRC's website (www.itrc.org).

Table 1. Flushing times for emitter types

Model	Flushing Period	
	18-hr	48-hr
Bowsmith Fan-Jet L. Blue Nozzle #40 PC-8 Orange Diaphragm	X	X
Bowsmith Fan-Jet Yellow Nozzle #55 PC-14 Purple Diaphragm	X	X
Eurodrip PC^2 Hose, with Emitters	X	
Eurodrip Corona 0.5 GPH		X
Jain Microsprayer AquaSmart 2002 Orange Nozzle		X
Jain Microsprayer AquaSmart 2002 Violet Nozzle		X
Jain Clicktif Emitter Brown Outlet	X	X
Jain Clicktif Emitter Black Outlet	X	X
Jain Flipper Black Nozzle		X
Jain Dan-Jet 12-JTX Blue Nozzle		X
Jain Eliminator (Orange)		X
John Deere Supertif Brown	X	X
John Deere S2000 Microsprinkler, Black Nozzle		X
John Deere S2000 Microsprinkler, Blue Nozzle	X	X
Netafim Emitter 01PC2, Red, Big	X	
Netafim Emitter 01PC4, Black, Big	X	
Netafim Emitter 01WPC8, Green, Big	X	X
Netafim Emitter 01WPCJL2, Red, Small	X	X
Netafim Emitter 01WPCJL4, Gray, Small	X	X
Netafim Emitter 01WPCJL8, Green, Small	X	X
Netafim SuperNet		X
Netafim Techline 560 Hose Brown		X
Netafim Techline CV Hose Brown		X
Olson Irrigation Vibra-Clean Emitter, Blue	X	X
Plastro HydroPC	X	
RainBird AG A5	X	
Toro Drip In PC		X
Toro Waterbird VI-PC L. Green		X

ITRC conducted two tests to measure the performance and manufacturing characteristics of pressure-compensating emitting devices based upon the points above. The two tests are described below.

Test 1 – Flow vs. Pressure

Groups of 30 emitting device samples were installed on a test bench and pressurized. The emitter discharges from all 30 emitters were combined, and the collected volume was divided by 30 to obtain the average emitter flow rate at a variety of emitter inlet pressures.

A sample flow-vs.-pressure graph from the manufacturer EurodripUSA for the Corona emitter is shown in Figure 1, which shows a constant, straight line of flow rate after the pressure compensation begins. Although this sample graph can be described as an exception, many manufacturers publish perfectly straight flow-vs.-pressure curves for all emitter models, which may or may not describe in-field performance. A flow-vs.-pressure graph from another Netafim emitter model, as measured by ITRC Test 1, is shown in Figure 2.

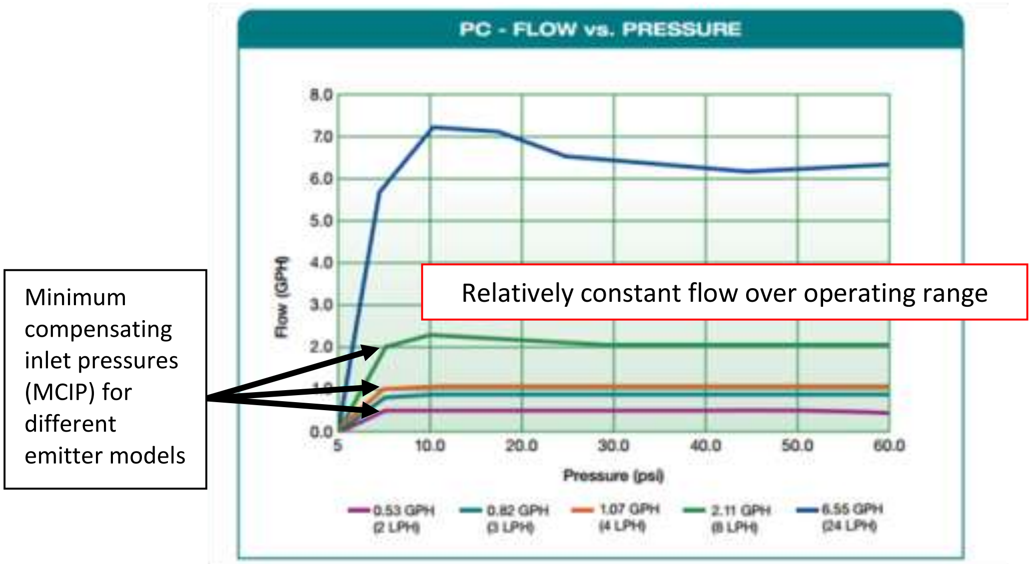

Figure 1. Sample manufacturer graph of emitter discharges over a range of inlet pressures (from Eurodrip USA)

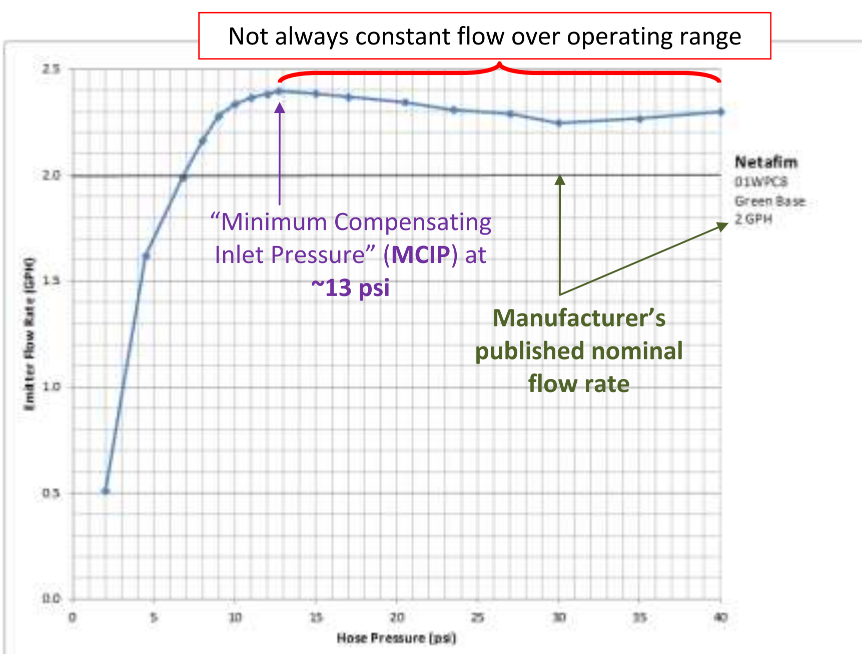

Figure 2. Example graph to illustrate key test items. It should be noted that most of the Netafim products showed excellent results.

The graphs show three important performance characteristics quantified in Test 1:

1. The Minimum Compensating Inlet Pressure (MCIP) of the emitter, which is the pressure at which the emitter begins to compensate for emitter inlet pressure in order to maintain a constant flow rate. On the graph, this should be the point at which the dotted line flattens out. The exact MCIP is somewhat subjective because of the nature of the curves.
2. The ability of the emitting device to meet its nominal flow rate. On the graph, this is determined by the dotted line's distance above or below the straight black line of the nominal flow rate.
3. The ability of the emitting device to maintain a consistent flow rate throughout a low pressure operating range. On the graph, this is represented by the amount that the dotted line fluctuates at pressures above the MCIP.

Test 2 – Coefficient of Variation due to Manufacturing (cv)

Many manufacturers also publish cv values for emitting devices that reflect the discharge flow variability due to manufacturing tolerances. This value is computed using the following formula:

$$cv = \frac{standard\ deviation}{mean} \qquad \text{(Eq. 1)}$$

Where,

Standard deviation is the standard deviation of individual emitter discharges
Mean is the arithmetic mean of individual emitter discharges

ITRC tested each emitting device using the same test stand from **Test 1**, but collected the volumes from each individual emitter to calculate the cv. During testing, several of the medium and high flow models tested had one emitter out of the total group of 30 tested emitters that would emit significantly higher flows than the other 29 of the same model. These "faulty" emitters had a measureable effect on the cv values for those models. In summary Table 2, models that had a faulty emitter in the test group are denoted by an asterisk (*).

Table 2. Emitter performance comparison between manufacturer specifications and ITRC measurements

		MCIP, psi[1]		Average Compensated Flow Rate, GPH			Manuf. cv	
Manufacturer	Description	From ITRC test curve	From manufacturer curve	Published	Actual[2]	% Difference	at Lower P[3]	at Higher P[4]
Bowsmith	Fan-Jet L. Blue Nozzle #40 PC-8 Orange Diaphragm	15.5	13	8	7.1	-12.7%	0.026	0.034
Bowsmith	Fan-Jet Yellow Nozzle #55 PC-14 Purple Diaphragm	18.3	18	14	13.3	-5.3%	0.023	0.027
Eurodrip	PC[2] Hose, with emitters	6	5	0.5	0.5	0.0%	0.055	0.078
Eurodrip	Corona 0.5 GPH	7.3	7.5	0.5	0.54	7.4%	0.024	0.018
Jain	Microsprayer 2002 AquaSmart	25	15	18.5	18.5	0.0%	0.055	0.069

	Orange Nozzle							
Jain	Microsprayer 2002 AquaSmart Violet Nozzle	22	15	5.28	5.2	-1.5%	0.019	0.019
Jain	Clicktif Emitter Brown Outlet	9.2	10	0.5	0.48	-4.2%	0.020	0.026
Jain	Clicktif Emitter Black Outlet	9	10	1	1.01	1.0%	0.021	0.030
Jain	Flipper (Black Nozzle)	>50	35	6.6	6.58	-0.3%	0.036	0.037
Jain	Dan-Jet 12-JTX Blue Nozzle	30	15	10	10.7	6.9%	0.188*	0.106*
Jain	Eliminator (Orange)	25	22	18.5	19.4	4.6%	0.161*	0.176*
John Deere	Supertif Brown	9	9	0.58	0.61	4.9%	0.026	0.040
John Deere	S2000 Microsprinkler, Black Nozzle	27	29	6.3	5.47	-15.2%	0.038	0.013
John Deere	S2000 Microsprinkler, Blue Nozzle	28	29	8.2	8.4	2.4%	0.024	0.028
Netafim	Emitter 01PC2, Red, Big	7	5	0.5	0.53	5.7%	0.022**	0.024**
Netafim	Emitter 01PC4, Black, Big	10	7	1	1.04	3.8%	0.022**	0.031**
Netafim	Emitter 01WPC8, Green, Big	12.7	9	2	2.31	13.4%	0.033	0.032
Netafim	Emitter 01WPCJL2, Red, Small	7	5	0.5	0.53	5.7%	0.270	0.036
Netafim	Emitter 01WPCJL4, Gray, Small	8	5	1	1	0.0%	0.063*	0.066*
Netafim	Emitter 01WPCJL8, Green, Small	7	9	2	2.04	2.0%	0.057	0.031
Netafim	SuperNet	32	22	5.3	5.81	8.8%	0.048*	0.058*
Netafim	Techline 560 Hose Brown	9	5.9	0.53	0.57	7.0%	0.022	0.026
Netafim	Techline CV Hose Brown	13.2	7.5	0.61	0.57	-7.0%	0.018	0.023
Olson Irrig.	Vibra-Clean Emitter, Blue	10	5	1	1	0.0%	0.021	0.049*
Plastro	HydroPC	10	11.8	0.95	0.85	-11.8%	0.047**	0.049**
RainBird	AG A5	6	7	0.53	0.53	0.0%	0.020	0.040
Toro	Drip In PC	11	15	0.5	0.56	10.7%	0.079	0.070
Toro	Waterbird VI-PC L. Green	23	22	14.5	13.65	-6.2%	0.035	0.037

[1] Estimation of the lowest emitter inlet pressure at which pressure compensation appeared to begin
[2] Minimum Compensating Inlet Pressure (MCIP): computed as weighted average GPH between the minimum inlet pressure and 15 psi above the minimum pressure
[3] The cv of 30 emitters at approximately 3 psi greater than the minimum pressure
[4] The cv of 30 emitters at 10 psi greater than the lower pressure cv
* One emitter of this model was identified as faulty. It is likely the cv would be substantially different if that emitter had functioned properly
** Three models were tested after operating for a minimum of 18 hours; the remaining models were operated for 48 hours before testing.

Conclusion

The test results indicate the following conclusions:

1. The majority of ~0.5 gallon-per-hour (GPH) emitters, regardless of manufacturer, exhibited:

    a. Excellent cv (< 0.03) values
    b. Low Minimum compensation inlet pressures (< 10 psi)
    c. Consistent flow rates within the nominal operating pressure range
2. The percentage of well-performing products decreases as the flow rate increases. Few microsprayers had excellent PC performance.
3. Observations during the testing identified some potential causes for individual emitter flow rate fluctuations. Although these performance characteristics were outside of the scope of this project and thus not quantified, they may be practical topics for future research. The characteristics include:
    a. *Repeatability*. Variation caused by cycling inlet pressure ON and OFF
    b. *Duration of pressurization*. While the average emitter flow rate tended to remain constant, some models exhibited an increase in discharge flow rate variation the longer they stayed under pressure.
4. With several models, a single emitter out of the total test group of 30 would exhibit a substantially higher discharge flow rate than the average of the other same-model emitters. These faulty emitters had a measureable effect on the cv values for those models.

Graphs of results can be found in Figures 3-7.

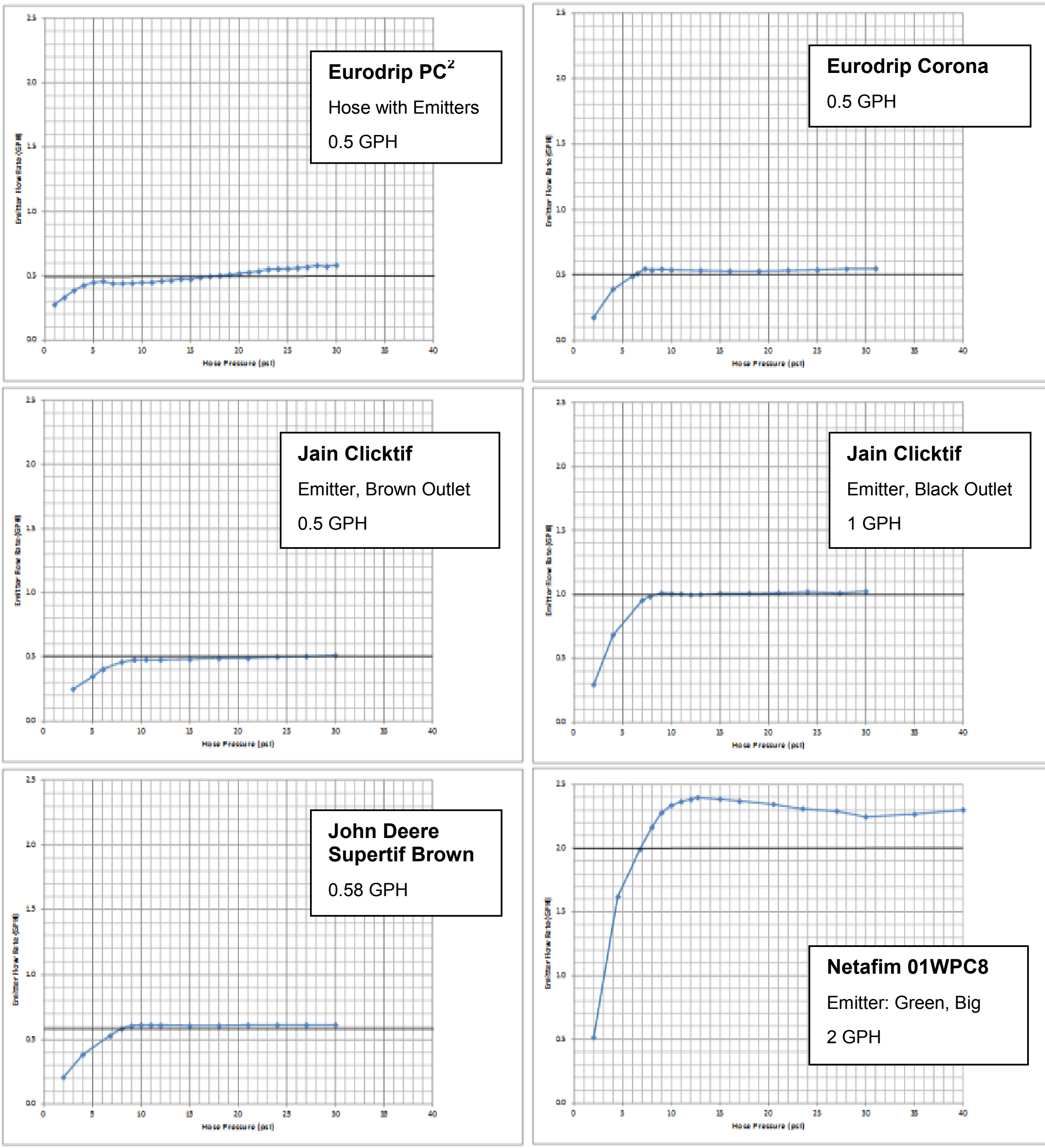

Figure 3. Flow regulation at various inlet pressures with <u>low</u> flow emitters

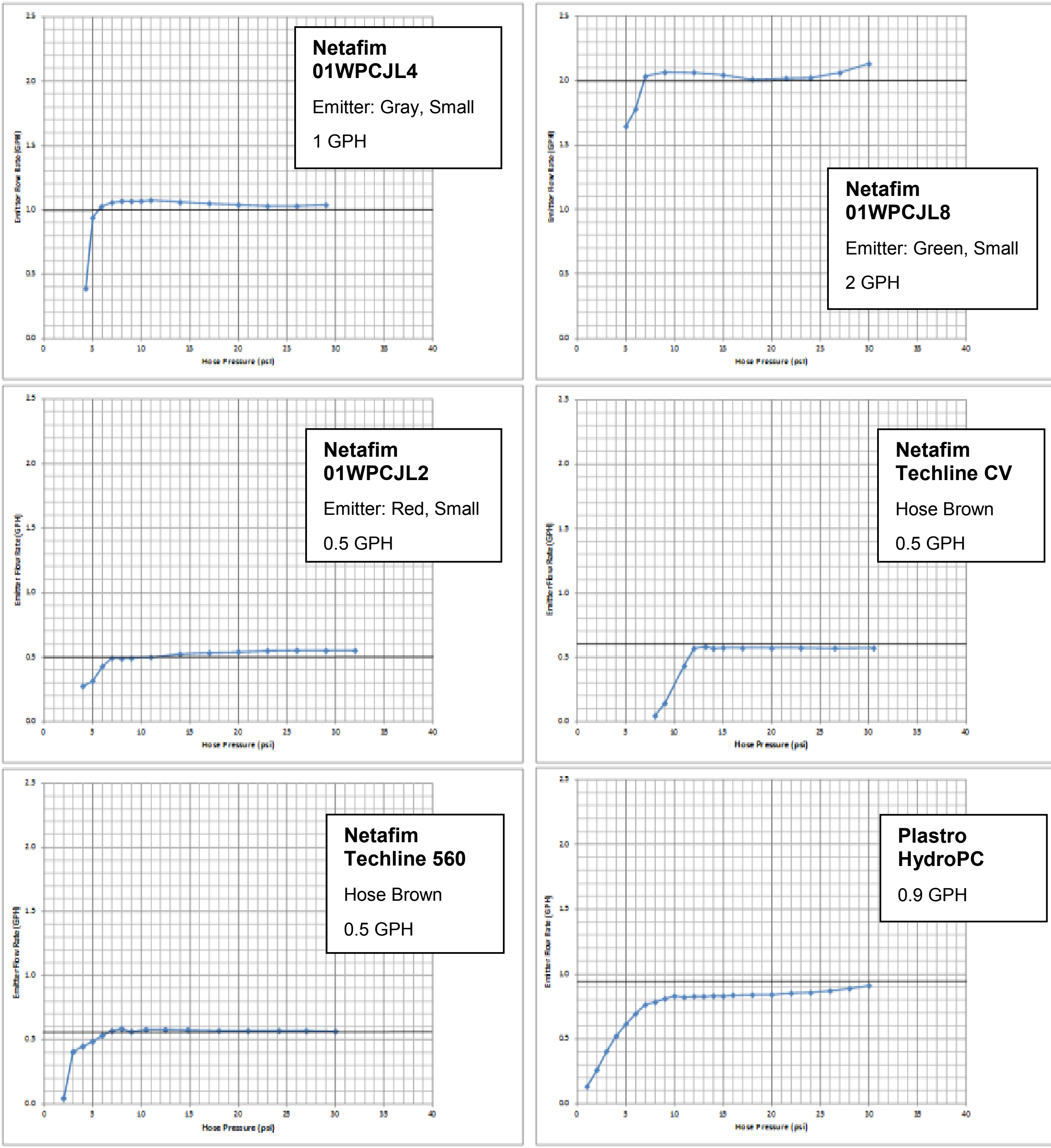

Figure 4. Flow regulation at various inlet pressures with <u>low</u> flow emitters (2)

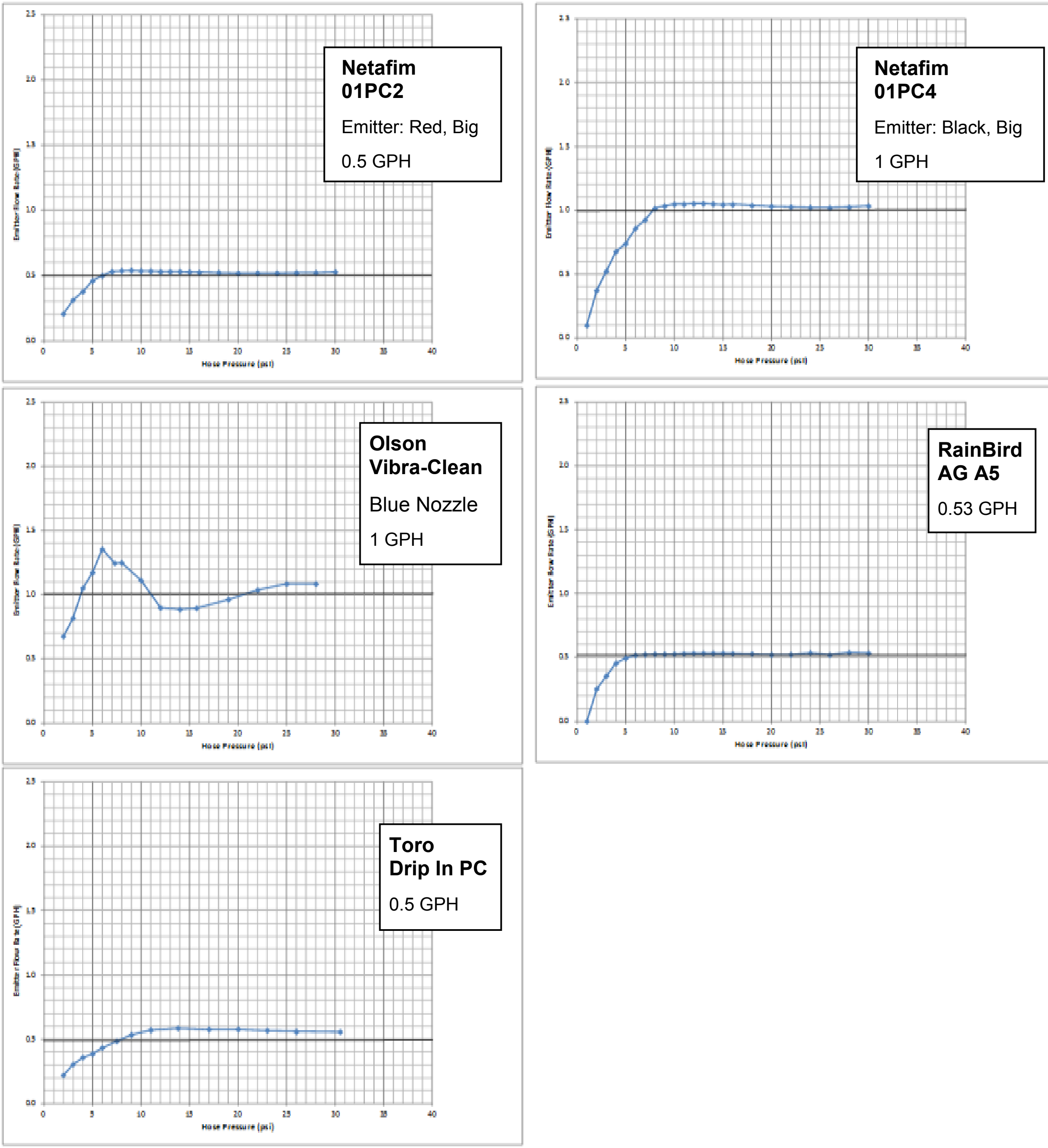

Figure 5. Flow regulation at various inlet pressures with low flow emitters (3)

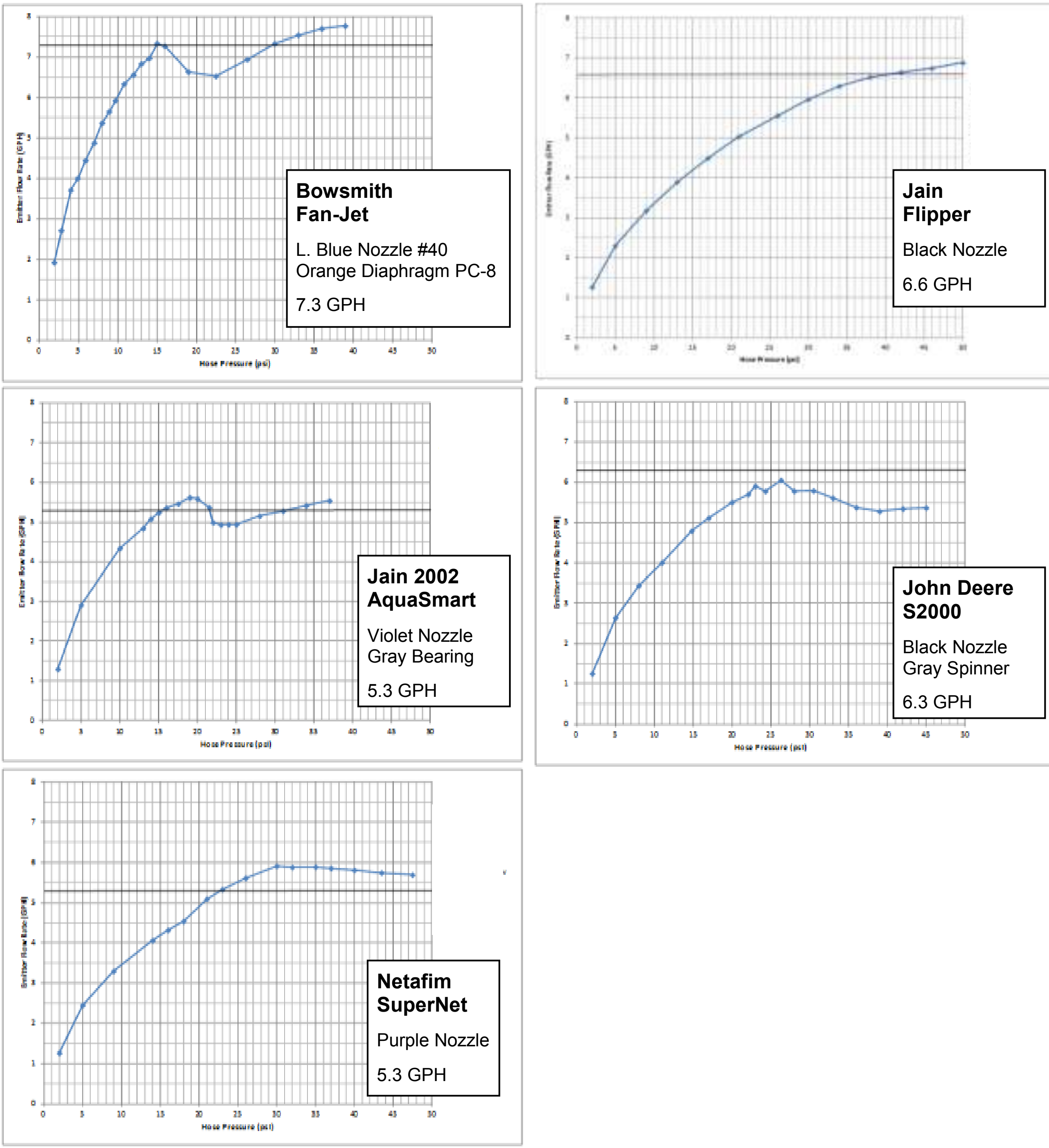

Figure 6. Flow regulation at various inlet pressures with <u>medium</u> flow emitters

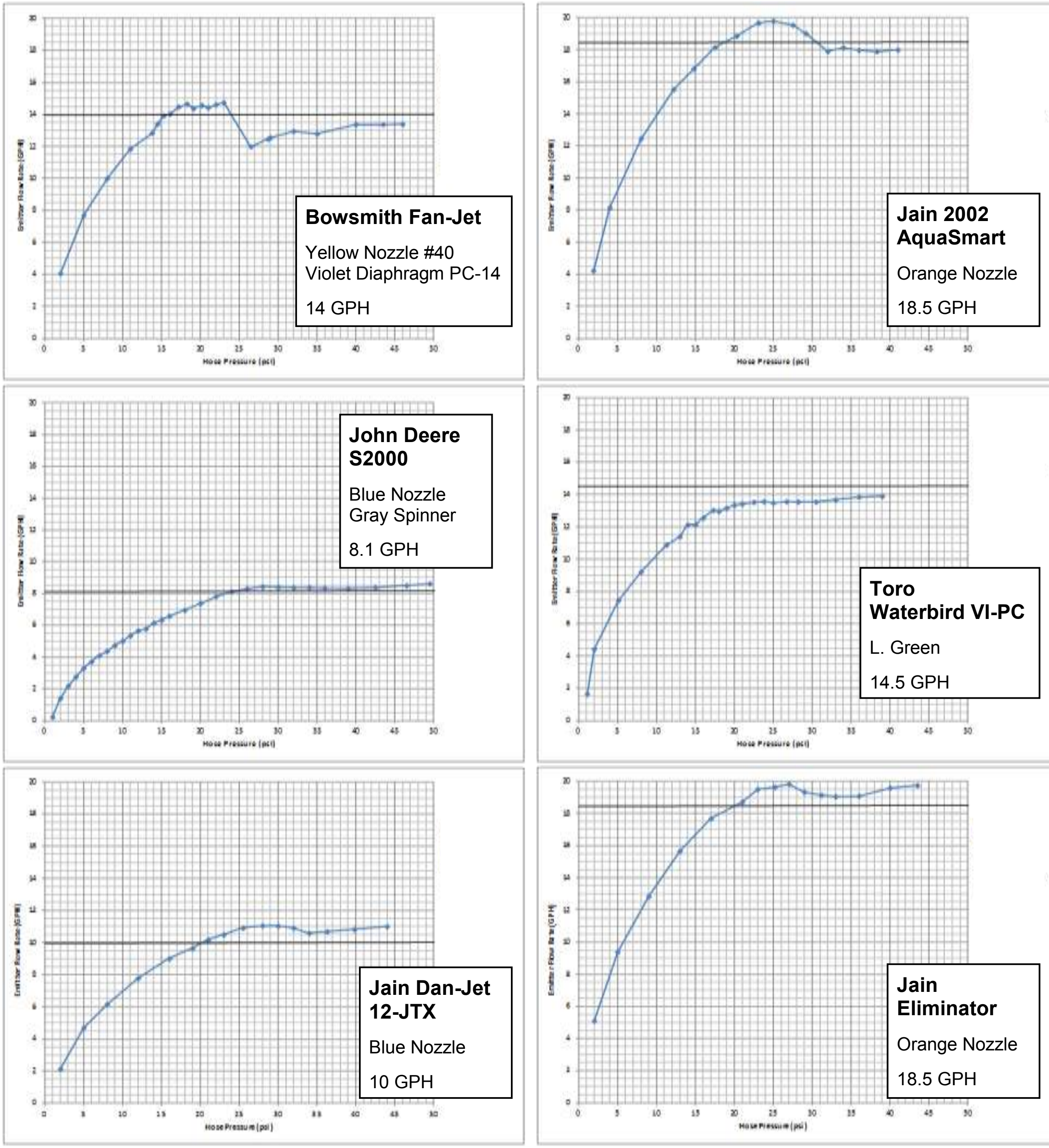

Figure 7. Flow regulation at various inlet pressures with high flow emitters

Thriving in Drought with Subsurface Drip Irrigation (SDI): Case Studies and Tools

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Abstract. *As the worst drought in 50 years gripped America's farmland in the summer of 2012, three Nebraska producers reported increased soybean yields and significantly lower water use at the same time by using Subsurface Drip Irrigation (SDI) to deliver water and nutrients directly to the roots of their crops. This was in contrast to the typical practice of applying water to the surface with gravity or sprinkler irrigation systems. In addition to improved yields and resource use efficiency (RUE), other benefits cited included an improved ability to farm in drought conditions, improved flexibility and improved convenience. In each of these case studies, the producer found SDI a worthwhile investment.*

Considering the potential benefits of SDI, Toro has developed several tools that help producers with the transition. First, the Drip/Micro Payback Wizard is an online calculator that estimates how long it will take to pay for an investment in SDI by comparing before and after yield and production financial data. In addition, it estimates how many additional acres may be farmed with the water saved by adopting SDI. Second, AquaFlow Drip Irrigation Design Software allows users to quickly and easily design a drip irrigation system by entering field parameters and then selecting appropriate laterals, sub-mains and mainlines. Third, the 129-page, four-color, fully illustrated second edition of Toro's Drip Irrigation Owner's Manual is available in both English and Spanish, with measurements in English and metric units. All of these tools are available for free download from toro.com and driptips.toro.com.

Keywords. *Subsurface Drip Irrigation (SDI), Drought, Drip Irrigation Economics, Drip Irrigation Design, Drip Irrigation Operation and Maintenance.*

Introduction

Micro-Irrigation, also commonly called drip irrigation, is the fastest growing irrigation technology in the Unites States. It was commercially introduced over four decades ago, and its usage has since spread to 3.5 million acres of diversified farmland throughout the US as of 2008 (USDA, 2008). Documented case studies have shown that farmers adopt drip irrigation for a variety of reasons, including improved crop response from the spoon feeding of water and nutrients directly to the crop's rootzone, and improved resource use efficiencies. These benefits often boost farm income and reduce irrigation related production costs enough to pay for the investment quickly. In addition, runoff, wind drift and deep percolation of irrigation water is minimized, and access to the field is improved compared to other irrigation methods (Toro Grower Solutions, 2007-2012). Figure 1 graphically describes these typical benefits (Corcos, 2012).

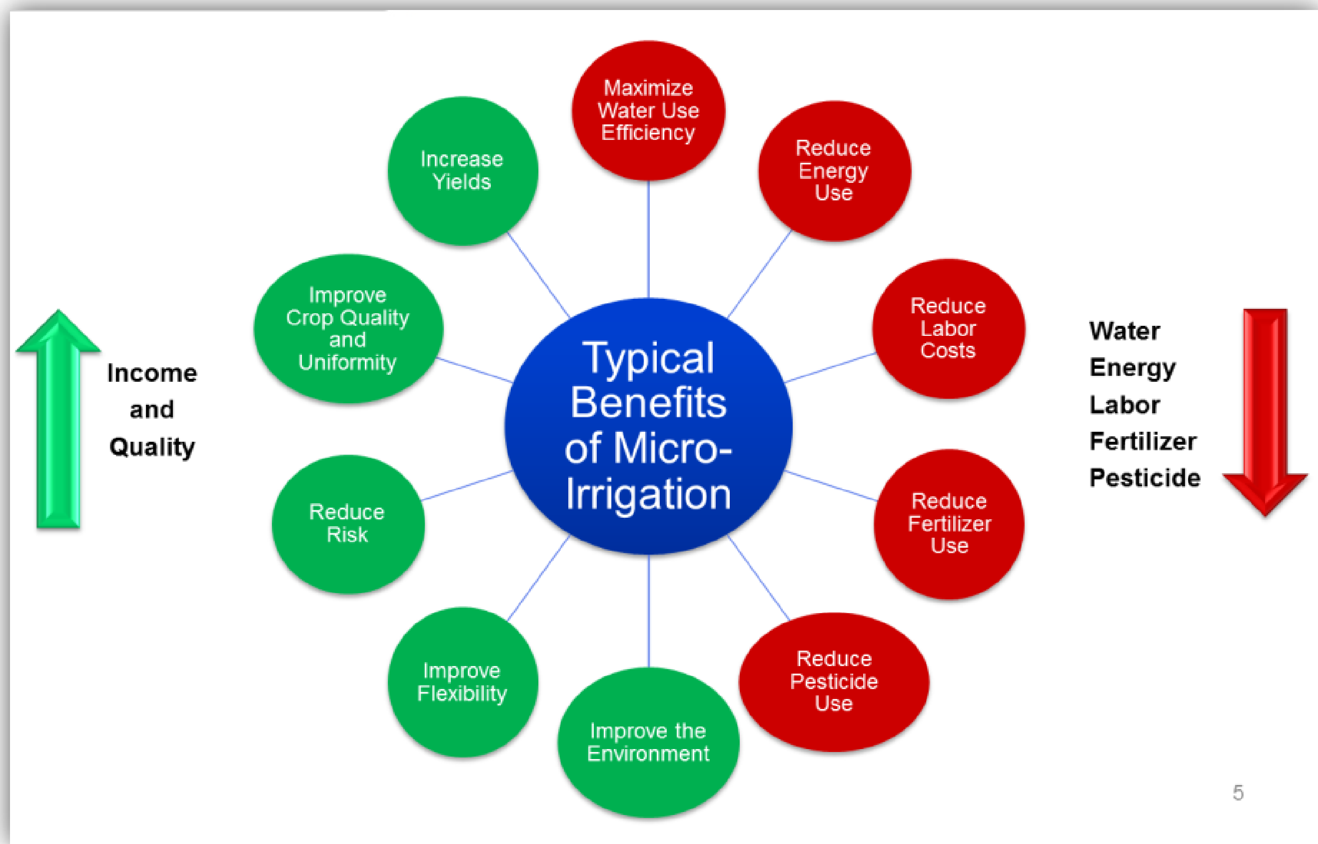

Figure 1 - Typical Benefits of Micro-Irrigation showing increased income and quality, and decreased water, energy, labor, fertilizer and pesticide costs.

Drip irrigation differs from gravity and sprinkler irrigation in a number of ways. A drip system consists of a network of plastic pipes and emission devices that deliver pressurized water directly to the soil at a low pressure and low flow rate. It is typically operated at frequent intervals, and the duration of operation may be adjusted to accomplish numerous changing objectives. The system is flexible and may accommodate a wide range of block sizes and shapes and flow rates. Source water is filtered to prevent clogging of drip system emission devices, and chemical injection systems are used to apply fertilizers, crop protection materials and drip system maintenance chemicals (Stetson, 2011). Figure 2 shows a Typical Drip System Layout for field crops (corn shown), row/vegetable crops (lettuce shown), vineyards and orchards (almond trees shown). (Toro, 2012).

Subsurface Drip Irrigation (SDI), the topic of this paper, is a specialized sub-set of drip irrigation where lateral lines are buried beneath the soil surface. In the case of SDI for field crops such as soybeans, corn, cotton and alfalfa, drip tape laterals are buried 6 – 18 inches deep and are connected to sub-mains that are buried 2 to 3 feet deep and remain undisturbed for many years. Research at Kansas State University has shown that these systems are capable of performing well for over 20 years without replacement and that “annual system performance evaluations have shown that dripline flowrates are within 5% of their original values.” (Lamm, et al 2011). This longevity enhances the economic viability of drip for crops that typically have lower profit potential in comparison with the fruit, nut and vegetable crops that have historically adopted drip first. The graphic at the bottom left of

Figure 2 is a good example of how SDI systems are configured for the soybean crops that are described in the following case studies.

n the course of documenting the following three case studies from the state of Nebraska, it becomes apparent that the benefits of drip for soybeans, a field crop, in this drought stricken region are somewhat different than those usually cited for fruit, nut and vegetable crops, or even field crops, in non-drought stricken areas. While yield increases and resource use efficiency are common benefits of using drip irrigation in numerous crop situations, these producers especially appreciated the improved ability to farm in drought conditions using SDI, as well as the SDI system's flexibility and convenience. As a result, the contents of the "Benefits of SDI" as shown later in Figure 5 are different than the "Typical Benefits of Micro-Irrigation" shown in Figure 1.

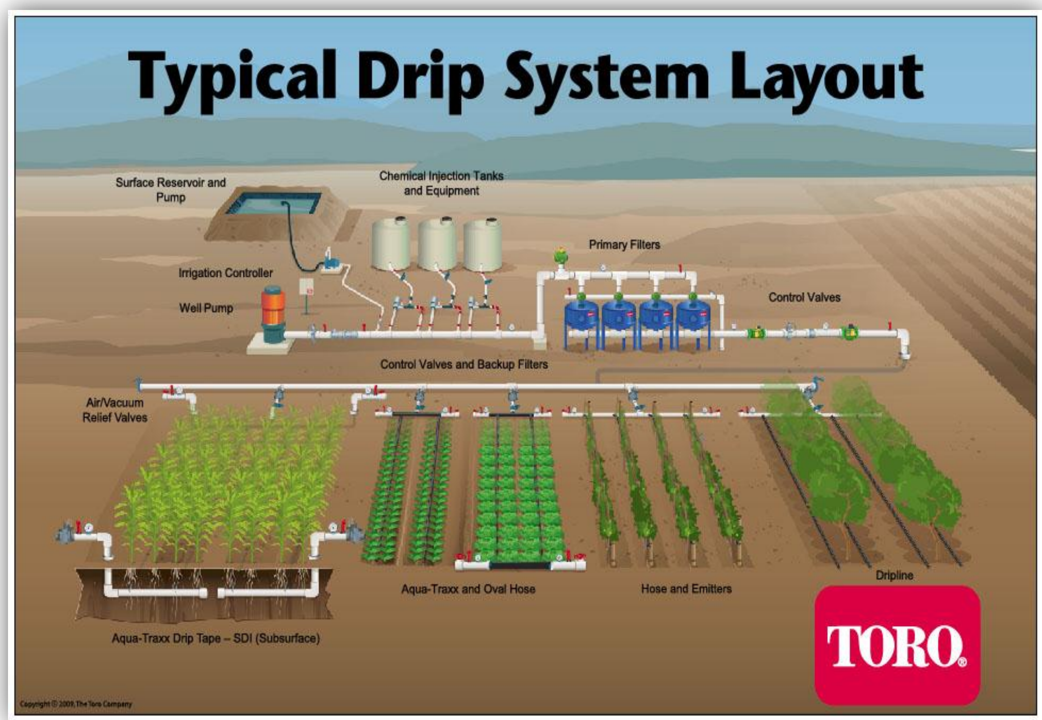

Figure 2 - Typical Drip System Layout showing how drip is used in field and vegetable crops, and orchards and vineyards.

Case Studies

As the worst drought in 50 years gripped America's farmland in the summer of 2012 and crop failure was rampant, three Nebraska producers reported increased soybean yields and significantly lower water use at the same time by using Subsurface Drip Irrigation (SDI) to deliver water and nutrients directly to the roots of their crops. This was in contrast to the typical practice of applying water to the surface with gravity or sprinkler irrigation systems. In addition to improved yields and resource use efficiency (RUE), other benefits cited included an improved ability to farm in drought conditions, improved flexibility and improved convenience. In each of these case studies, the producer found SDI a worthwhile investment. Following is a summary of their experiences as shared with Toro by interview on August 16 and 17th, 2012 and published by Toro and others shortly afterwards (Farm Progress, AgriMarketing, 2012).

Ken Seim Farms, Grand Island, NE area

Ken Seim of Grand Island, Nebraska, has farmed 1,400 acres of corn and soybeans for over 35 years. Currently, he farms 100 acres with SDI; 13 acres on 4th year and 87 acres on 2nd year. In addition, he has 1,300 acres under pivot irrigation. His first SDI system was installed to replace a labor intensive gravity pipe field. A pivot would have left a 13 acre parcel un-irrigated due to the obstruction caused by a home, thus was a less attractive option.

As of August 16, 2012, Seim reported that in addition to 3.5 inches of rainfall, he had only applied 9 inches of water to the SDI field to achieve the same yields as the field where he had applied 20 inches of water with a center pivot irrigation system; his gravity fields received 22 inches of water. The improved water use efficiency with SDI is attributed in part to the lack of evaporation that occurs with flood and sprinkler irrigation. Seims believes the application uniformity on his gravity fields is about 40 percent, on his pivot fields between 60-70 percent, and on his drip fields over 90 percent.

In addition to the improved efficiency of using drip vs. gravity or pivot irrigation, Seims reports that SDI blocks can be more easily sized to match the available water source, which is very important as aquifers and well production decline. This is in contrast to other irrigation methods which require a minimum amount of flow to operate – in many cases, the required flow is no longer available. Seims believes that in the future, groundwater supplies will be reduced just as surface water supplies already have been. For example, two of his wells used to provide 1,600 gpm and now they are only providing 400 gpm, which is not sufficient flow to operate a pivot. SDI blocks may also be successfully configured to irrigate half mile runs, a challenge for gravity irrigation systems.

Seims also reported that his labor costs with SDI are about one-third compared with flood, but are about the same as a pivot. However, SDI labor requirements occur in the spring when repairs are easier to perform and less detrimental to the crop. In contrast, pivot repairs occur in the middle of the summer when tall crops make gear box repairs difficult.

Seims noted that one of his biggest challenges was determining when to irrigate since the soil surface was dry. He uses soil probes and sensors, and will be experimenting with capacitance sensors in the future.

Finally, Seims reports that adopting SDI was easy with excellent dealer and manufacturer support. He believes that “efficient subsurface drip Irrigation is the future of irrigation, and that the adoption rate of SDI technology is rapidly rising. Producers will have to invest in technology to remain efficient and productive - we want to be proactive, not reactive.”

Gary Greving Farms, Grand Island, NE area

Gary Greving farms 1,100 acres mostly with pivots. He installed 10 acres of drip 4 years ago, and installed another 18 acres of drip 2 years ago. He adopted drip primarily to reduce labor costs, which ended up being equal compared to pivots, but unexpectedly experienced other benefits including reduced water use, yield increases and improved field accessibility.

His first year soybean yields were 7-8 bushels per acre better. At a value of $8/bu, that equated to $56 - $64/acre increased income. Since then, he has increased yields 40 percent using SDI, primarily because he has achieved tremendous plant health. “The stem of the plant was twice as thick, the leaf area larger, the plant taller, and the pod count over double (for pods that would produce two or more beans).”

Figure 3 was photographed on August 21, 2012 and shows that the SDI irrigated soybean plant on the top measured 48 inches long and received 9 inches of irrigation while the pivot irrigated plant on the bottom measured 36 inches long and received 22 inches of irrigation. Figure 4 shows the fields where the plants were growing: the soybean plants on the right were irrigated with SDI, the plants on the left with a center pivot.

Figure 3 – The SDI irrigated soybean plant on the top measured 48 inches long and received 9 inches of irrigation while the pivot irrigated plant on the bottom measured 36 inches long and received 22 inches of irrigation.

Figure 4 – Fields where the plants in Figure 3 were growing: the soybean plants on the right were irrigated with SDI, the plants on the left with a center pivot.

In addition to the 40% increase in yields, 60% less water was applied to the SDI field than the adjacent pivot field: the SDI fields received 9 inches of water while the pivot fields received 22 inches. Greving believes that as water supplies tighten, the investment in SDI may spell the difference between farming and not farming. "If we are only allocated 9 inches of water a year, as we already are in some parts of the state, we will have to irrigate with SDI in order to produce a crop. You can't grow a crop with 9 inches of water using pivots or gravity irrigation."

Greving noted that there is a learning curve with new technology, but that once he mastered SDI he found it was easier to use than pivots and was as close to 100 percent efficient as possible. Due to the improved water use efficiency with the SDI system, he typically irrigated 4 days each week instead of 7 with the pivot, and at a much lower pressure. This saved water, energy and labor. Finally, field accessibility was improved since the SDI fields have no obstructions, while pivot or gated pipe fields always have something in the way that has to be moved in order to perform field activities.

Don Anthony Farms, Lexington, NE area

Don Anthony has farmed 1,300 acres in the Platte Valley for over 40 years using gated pipe, pivots and now, SDI. He uses 2/3 to 3/4 the water and energy with SDI versus a center pivot. "If 1.0 inch of water is applied via a pivot, only 0.6 inches is beneficially or effectively used by the plant. Drip is more efficient." In addition to application efficiency, Anthony takes SDI one step further. "With SDI, I can 'play chicken' with the weather and sometimes take advantage of a rainfall event that I couldn't otherwise." Anthony explains that it takes 3 days for his pivots to complete an irrigation cycle, and over two weeks for his gravity fields. "With SDI, I can apply a small amount of water quickly and avoid plant stress. Therefore, I can wait longer for the rain and apply a short irrigation quickly if the rain doesn't come. If the rain does come, I have saved myself an irrigation cycle." Anthony is also using SDI to stretch limited water supplies so that all his land remains irrigated. "Since irrigated land has higher value, I have used SDI to avoid a balance sheet devaluation of my assets."

Anthony notes that fertigation with SDI is really fast, easy and efficient, too. "I have more options with SDI – I can fertigate a single block and easily track the results in a square sized block rather than a pie shaped block."

Regarding the investment, Anthony believes that producers have enjoyed great crop production over the past ten years, and that they have always had to reinvest during the good times in order to get through the tough times. "I am investing in pivots and drip now – both technologies have their place. There's not much to it – I have good local support."

Summary

In summary, each of these established Nebraska producers experienced substantial benefits using SDI. In all cases, water use efficiency was improved, i.e. substantially less water was applied to the crop vs. pivot or gravity systems to achieve the same, or even substantially higher, yields. Energy savings were also cited since the SDI system operated fewer hours, and at lower pressure, than pivots. Labor was equal to pivots, but was generally required in the spring when it was easier to perform and less detrimental to the crop. In addition, producers noted that SDI systems are easier to configure for lower and/or changing water supply flow rates, for odd-shaped fields and/or fields with obstructions, and for fields with long ½ mile runs. Also, SDI enables producers to successfully farm even if water allocations are reduced to 9 inches, and can also help producers wait and take advantage of a rainfall event by applying small amounts of water quickly in case rain doesn't occur. SDI also helps maintain "irrigated land" status by stretching limited water supplies over more acres of land. The producers also enjoyed ease of field access with SDI, and the ease by which fertilizers could be injected into the system either for the whole crop or for small, square block fertilizer trials. Finally, each producer cited excellent support from the local dealer and manufacturer of the SDI system. Table 1 describes these benefits in tabular form:

Table 1: Advantages of SDI on Soybeans during 2012 Crop Year - Nebraska, US

	Seims	Greving	Anthony
Farmed Acres	1,400	1,100	1,300
Acres of SDI	100	28	250
Inches of rainfall	3.5	3.5	
Inches applied with SDI	9	9	2/3 - 3/4 vs. pivots
Inches applied with pivots	20	22	
Inches applied with gravity	22		
Soybean Yields	Same as pivot	Increased 40%	
Labor	1/3 vs gravity; same as pivot	Same as pivot	
Energy		SDI runs 4 days per week instead of 7 and at lower pressure than pivot	2/3 - 3/4 vs. pivots
Can more easily configure an SDI system to:			
Fit changing/lower flow rates in the water supply	✓		
Efficiently irrigate 1/2 mile runs (vs. gravity)	✓		
Accommodate odd-shaped fields or obstructions	✓		
Crop may be produced with 9 inches of water		✓	
Can quickly apply a small amount of water if needed to take advantage of a rain event			✓
Stretch limited water supplies over more acres to maintain "irrigated status" on more land.			✓
Ease of fertigation, and fertigation trials			✓
Labor comes at an easier time of year	✓		
Field accessibility is improved		✓	
Excellent dealer and manufacturer support	✓	✓	✓

Figure 5 shows these benefits graphed on a wheel chart similar to Figure 1. When graphed in this manner, it is clear that the ability to farm in drought conditions, and increased flexibility and convenience, are important benefits of using SDI in field crops in addition to increased yields and reduced costs.

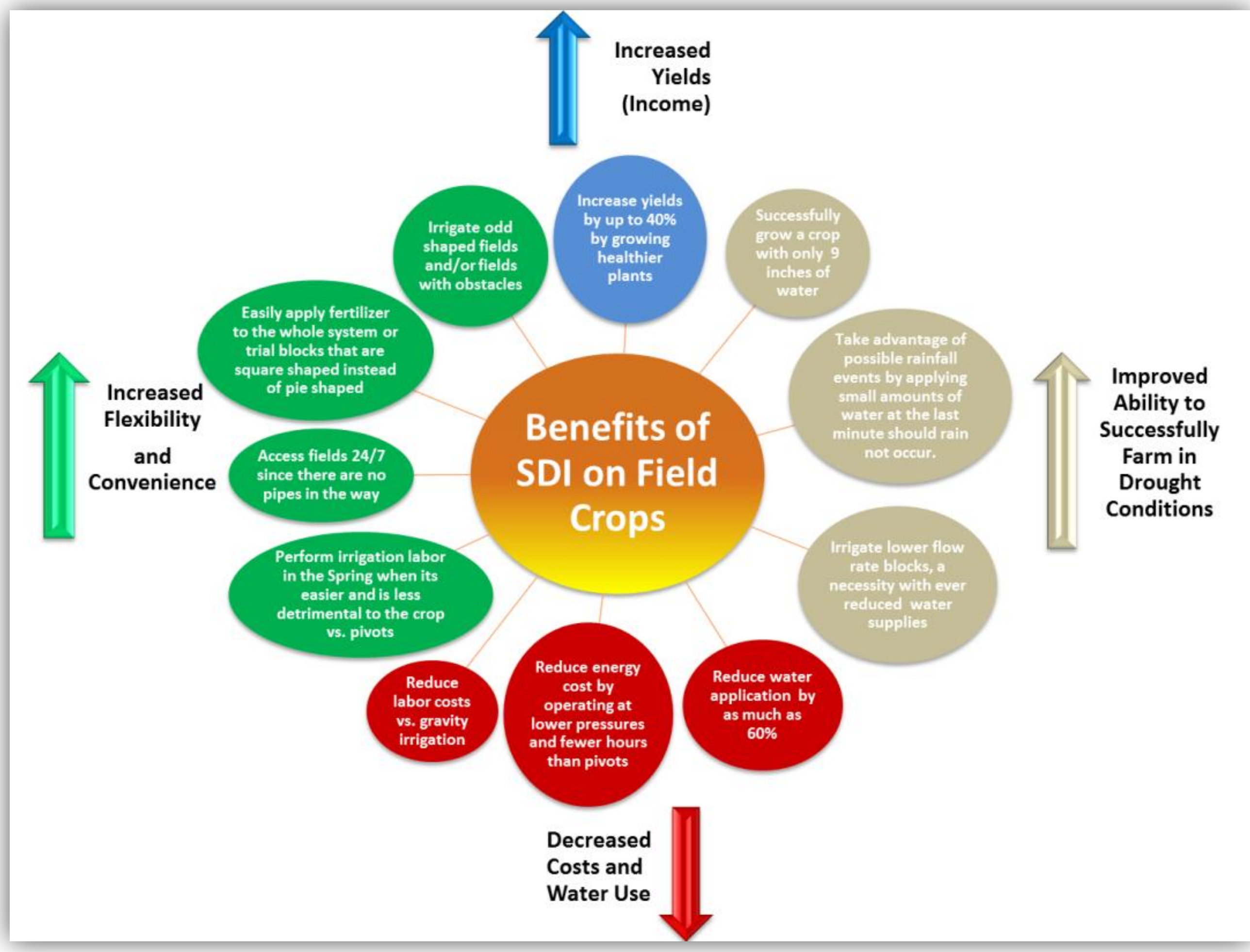

Figure 5 – Benefits of SDI on Field Crops. Note that these benefits are somewhat different than the "Typical Benefits of Micro-Irrigation" cited in Figure 1.

SDI Tools

Considering the potential benefits of SDI, Toro has developed several tools that help producers with the transition. First, the Drip/Micro Payback Wizard is an online calculator that estimates how long it will take to amortize an investment in SDI by comparing before and after yield and production financial data. In addition, it estimates how many additional acres may be farmed with the water saved by adopting SDI. Second, AquaFlow 3 Drip Irrigation Design Software allows users to quickly and easily design a drip irrigation system by entering field parameters and then selecting appropriate laterals, sub-mains and mainlines. AquaFlow's unique dashboard format displays system hydraulic parameters on one screen for both irrigation and flushing events, and includes a user friendly, color-coded uniformity map. Third, the second edition of Toro's Drip Irrigation Owner's Manual is available in both English and Spanish, with measurements in English and metric units. This 129-page, four-color, fully illustrated, spiral-wound document is a comprehensive guide to the operation and maintenance of both new and existing micro-irrigation systems for row, field and permanent crops. All of these tools are available for free download from toro.com and driptips.toro.com.

Drip-Micro Payback Wizard

As mentioned earlier, many case studies have shown that the investment in drip irrigation is often paid back in less than 3-5 years, sometimes less. The Drip Micro Payback Wizard was created to help producers easily estimate potential revenue increases and cost decreases that are normally associated with the adoption of drip irrigation so that they could evaluate whether the potential payback period was reasonable for their own operation. The Wizard also helps producers estimate how much water could be saved and/or how many additional acres could be farmed due to higher application uniformities associated with drip. If the results appear favorable, the producer may then decide to seek additional guidance from local government resources, academia, consultants, associations, equipment manufacturers or suppliers.

The Payback Wizard database is populated with estimated investment costs along with Cooperative Extension production cost, yield and revenue data for each crop in each of the 50 United States. After the crop, state, acres, current type of irrigation system and water cost per acre are entered by the user, the Payback Wizard reports the estimated payback period on the investment, and the additional acres that could be farmed with the water saved. This report may then be printed, or, the user can view and edit the detailed data to better reflect a specific production scenario. Figure 6, 7 and 8 are screen captures of Steps 1, 2 and 3 when using the Payback Wizard.

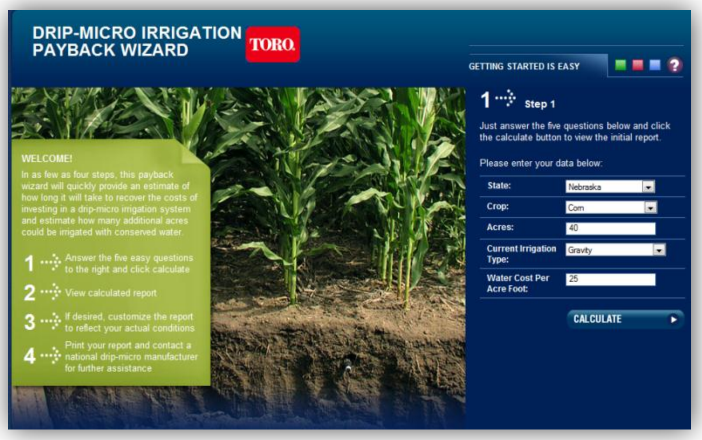

Figure 6 – Step 1 of the Payback Wizard

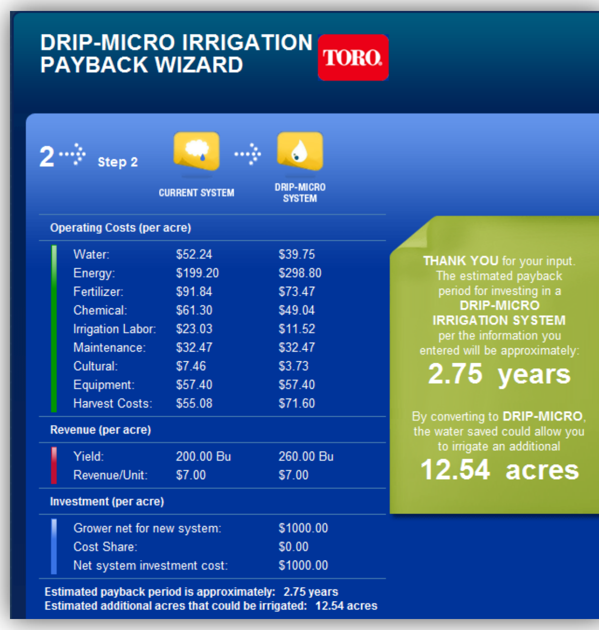

Figure 7 – Step 2 of the Payback Wizard

Figure 8– Step 3 of the Payback Wizard

Figures 6, 7 and 8 are screen captures of Steps 1, 2 and 3 when using the Payback Wizard. This example converts 40 acres of corn in Nebraska from gravity to drip irrigation assuming $25 per acre foot water costs. The payback period is estimated at 2.75 years, and it's estimated that an additional 12.54 acres could be irrigated with the conserved water. This estimate assumes a $1,000 per acre drip system investment cost, a 30% yield increase and a crop value of $7 per bushel. These are estimates only and do no guarantee results.

AquaFlow 3 Drip Irrigation Design Software

AquaFlow 3 is a new software program available for free download at toro.com upon approved registration. AquaFlow 3 features a unique dashboard which allows users to view changes to inputs instantaneously on one screen. This is in contrast to other design programs which require toggling between screens to view the results of lateral and submain irrigation and flushing design choices. Figure 9 shows the dashboard that appears immediately after launching the program from the desktop icon, and after selecting the Chart Tile function.

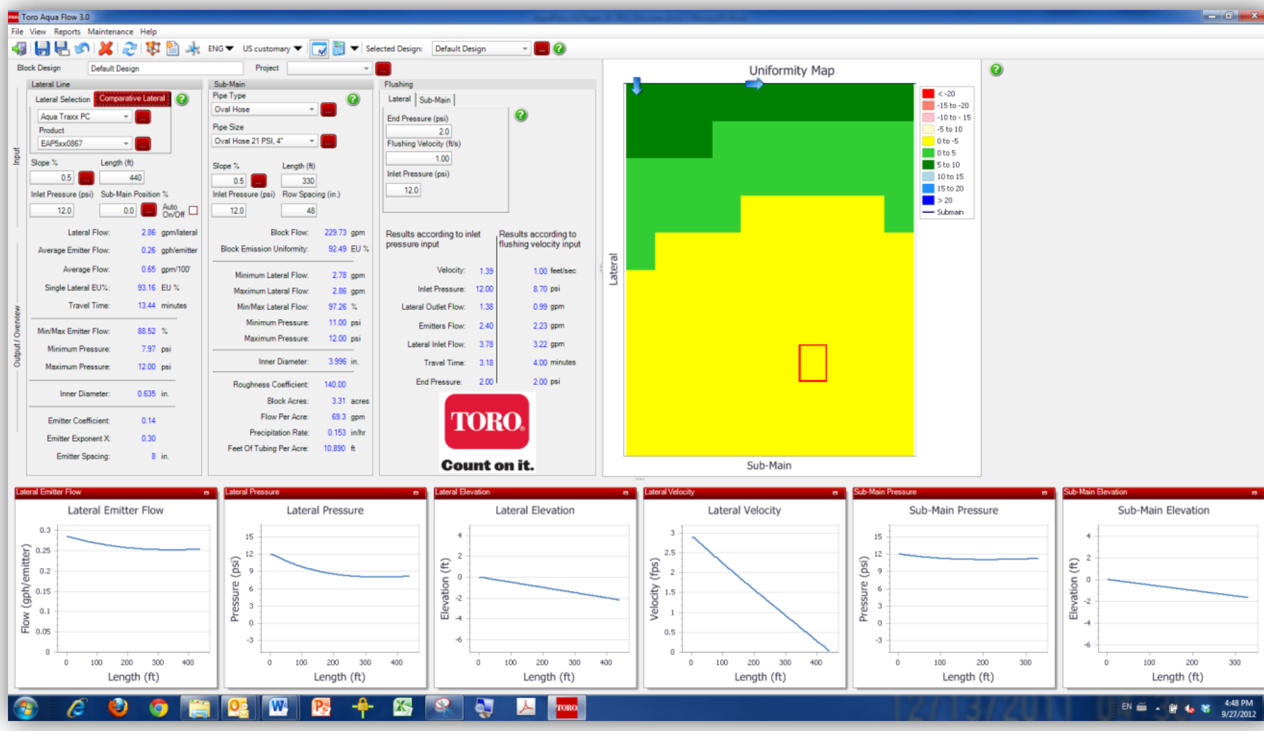

Figure 9 – AquaFlow 3 Drip Irrigation Design Software dashboard as it appears immediately after program launch and selection of the Chart Tile function.

AquaFlow supports a wide variety of lateral, submain and mainline pipeline choices and allows the entry of multiple slopes for each of them. In addition, sub-mains and mainlines may be telescoped. The results of design choices are readily displayed in tables, graphs, a color coded uniformity map, and in customizable reports that may be exported in a variety of formats such as pdf. Two different lateral choices may be easily compared as well, and sub-mains auto-positioned for maximum irrigation emission uniformity (EU). AquaFlow supports English and Spanish languages, and standard English and metric units.

AquaFlow is uniquely valuable to designers of SDI systems since SDI is expected to last for long periods of time and must be designed to be properly flushed. This aspect of design is often overlooked in some traditional short term drip irrigation systems. AquaFlow allows the designer to immediately view the results of lateral and sub-main design choices in terms of both the irrigation uniformity (such as EU) and the flushing parameters (velocity, inlet pressure and end pressure). This capability results in a more efficient design process and potentially better design results.

Figure 10 and 11 below show the cover and table of contents of this 129-page, four-color, fully illustrated, spiral-wound document. It is a comprehensive guide to the operation and maintenance of both new and existing micro-irrigation systems for row, field and permanent crops, including the operation and maintenance of SDI systems. It is available in both English and Spanish, with measurements in English and Metric Units.

Figure 10 – Cover of Toro Micro-Irrigation Owner's Manual.

Figure 11 – Table of Contents of 2nd Edition of Manual.

The Owner's Manual is especially useful for those who have adopted SDI systems since monitoring, flushing and maintenance are important to maximize the system's life expectancy. Figures 12, 13 and 14 are Owner's Manual illustrations of these concepts.

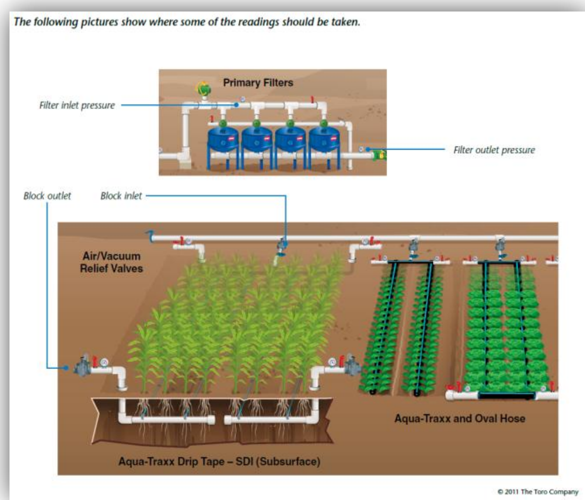

Figure 12 – Recommended pressure monitoring locations for SDI systems. Note that the flushing sub-main has been divided in half to facilitate proper flushing velocities.

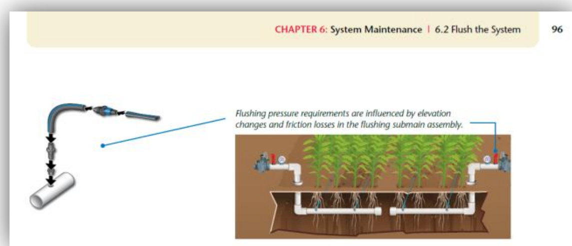

Figure 13 – Sub-main flushing details for an SDI system.

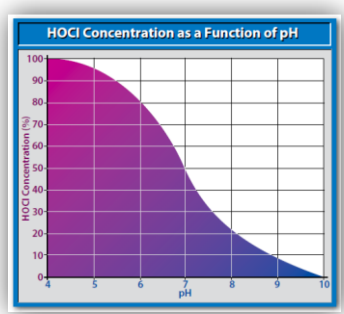

Figure 14 – HOCL concentration as a function of pH. Chlorine is often injected into SDI systems to control biological contaminants. Note that its efficacy is greatly reduced if the water pH is over 6.0.

Conclusion and Summary

In conclusion, the use of drip irrigation, and subsurface drip irrigation (SDI) in particular, is growing rapidly in the United States as a result of the many benefits that producers realize after adopting it. Three case studies document the positive experiences of three established producers who grew soybeans with SDI in Nebraska during the drought of 2012, the worst in fifty years. These producers reporter increased soybean yields and significantly lower water use at the same time using SDI to deliver water and nutrients directly to the roots of their crops. This was in contrast to the typical practice of applying water to the surface with gravity or sprinkler irrigation systems. In addition to improved yields and resource use efficiency (RUE), other benefits cited included an improved ability to farm in drought conditions, improved flexibility and improved convenience. In each of these case studies, the producer found SDI a worthwhile investment.

The specific benefits are listed in both chart and wheel graph form. Water use efficiency was improved, i.e. substantially less water was applied to the crop vs. pivot or gravity systems to achieve the same, or even substantially higher, yields. Energy savings were also cited since the SDI system operated fewer hours, and at lower pressure, than pivots. Labor was equal to pivots, but was generally required in the spring when it was easier to perform and less detrimental to the crop. In addition, producers noted that SDI systems were easier to configure for lower and/or changing water supply flow rates, for odd-shaped fields and/or fields with obstructions, and for fields with long ½ mile runs. Also, SDI enabled the producers to successfully farm even when water allocations were reduced to 9 inches, and helped producers wait and take advantage of rainfall events by allowing the application of small amounts of water quickly in case rain didn't occur. SDI also helped maintain "irrigated land" status by stretching limited water supplies over more acres of land. The producers also enjoyed ease of field access with SDI, and improved ease of crop fertilization since fertilizers could be injected into the system either for the whole crop or for small, square block fertilizer trials. Finally, each producer cited excellent support from the local dealer and manufacturer of the SDI system.

It is interesting to note that while yield increases and resource use efficiency are common benefits of using drip irrigation in numerous crop situations, these particular field crop producers especially appreciated the improved ability to farm in drought conditions using SDI, as well as the SDI system's flexibility and convenience. As a result, the contents of the "Benefits of SDI on Field Crops" wheel chart as shown in Figure 5 are different than the "Typical Benefits of Micro-Irrigation" wheel chart shown in Figure 1.

Considering the potential benefits of SDI, Toro has developed several tools that help producers with the transition. First, the Drip/Micro Payback Wizard is an online calculator that estimates how long it will take to amortize an investment in SDI by comparing before and after yield and production financial data. In addition, it estimates how many additional acres may be farmed with the water saved by adopting SDI. Second, AquaFlow 3 Drip Irrigation Design Software allows users to quickly and easily design a drip irrigation system by entering field parameters and then selecting appropriate laterals, sub-mains and mainlines. AquaFlow's unique dashboard format displays system hydraulic parameters on one screen for both irrigation and flushing events, and includes a user friendly, color-coded uniformity map. Third, the second edition of Toro's Drip Irrigation Owner's Manual is available in both English and Spanish, with measurements in English and metric units. This

129-page, four-color, fully illustrated, spiral-wound document is a comprehensive guide to the operation and maintenance of both new and existing micro-irrigation systems for row, field and permanent crops. All of these tools are available for free download from toro.com and driptips.toro.com.

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Chile root water uptake under partial root drying: a greenhouse drip irrigated study

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Abstract
Partial root drying (PRD) experiments were conducted in greenhouse to evaluate comparative effects of compensated and noncompensated (no water stress) root water uptake patterns for chile (NuMex Joe Parker*;* Capsicum annuum). *Three drip irrigation treatments used were: (1) control (fully irrigated), (2) PRD using vertically split-root system, and (3) PRD using two-compartment or lateral split-root system. In the vertically split system, water stress was applied to top 33% of the root zone whereas in the lateral split-root system alternate wetting and drying was imposed on each compartment. The two year experiment showed that chile plants under both PRD treatments with higher root length density and deeper rooting depth could compensate for water stress by taking up more water from the water available portion of the root-soil system to sustain transpiration or photosynthetic rates. Both PRD techniques have the potential for saving water in chile production especially for water limited arid environments.*

Keywords. Partial root drying, root water uptake, photosynthetic rate, transpiration rate

Introduction
Water is one of the principal limiting factors for plant growth and development in arid climates. In arid regions, the plant growth is sustained by irrigation using surface and ground water resources because of low and non-uniform distribution of rainfall. Since good quality freshwater is becoming increasing scarce, there is a growing need for development of efficient irrigation methods. PRD is one of the efficient irrigation methods in which water can be applied directly to the root zone. PRD techniques were successfully applied in Olive (*Olive europaea;* Badia et al., 2009), Tomato (*Solanum lycopersicum;* Zegbe et al., 2004), and Canola (*Brassica napus;* Mousavi et al., 2010). However, only few accounts are available for PRD in chile that has deeper root system (Deb et al., 2012). Therefore, the objective of this study was to evaluate root and plant growth and water usage of chile plants under PRD. Our hypothesis was that plant growth would be the same for PRD treatments and control.

Materials and Methods
Experimental set up

Fig. 1. Experimental set up

Experiments were carried out in the greenhouse (Fig. 1). New Mexican pod type chile (NuMex Joe E. Parker; *Capsicum annuum*) was sown on February 13, 2013. At eight leaf stage, seedlings were transplanted into containers (70 cm deep × 26 cm dia.) filled with sand, loam and organic matter in 1:1:1 by volume. Each pot was drip irrigated for 30 minutes on alternative days with flow rate of 2 Lh^{-1}. The drip irrigation treatments were Control in which water was applied by two emitters at surface using standard procedure, PRDv in which root zone was vertically divided and water applied by two emitters at 20 cm depth below surface, and PRDc in which root zone was divided laterally into two compartments and irrigated alternately using one emitter at a time. Completely randomized block design (CRBD) was used with three replications per treatment. To avoid edge effect and RLD determination two additional rows of plants were placed around treatment plants. Slow release fertilizer (Scotts Osmocote Classic) and liquid fertilizer (liquinox fish emulsion) were used as per the recoomendation.

Measurement of soil water content, soil temperature and meteorology

Two TDR sensors (Campbell Scientific, Inc., Logan, UT) at 0-30 and 30-60 cm for volumetric water content (θ) and two TMC6-HD sensors (Onset Computer Corp., Bourne, MA) at 5 and 25cm for soil temperature were installed in two containers per treatment. Air temperature, humidity sensor, and a net radiometer (Campbell Scientific, Inc., Logan, UT) were installed at 2 m above the bench. The Murray's equations (1967) were used for VPD calculations both inside and outside the greenhouse.

Plant Parameters

Photosynthetic rate, stomatal conductance, transpiration rate and leaf temperature were measured using LI-6400 XT portable photosynthesis system (LI-COR Biosciences, Lincoln, NE). These measurements were carried out on three fully expanded and exposed leaves per treatment between 800 h and 1100 h at two-week intervals. Plant height was measured manually and stem water potential (SWP) on bagged leaves was measured using Pressure Bomb (PMS Instrument Company, Albany OR-USA). Roots were washed manually and root images were scanned using Epson Perfection 3200 Photo flatbed scanner (Fig. 2a) and analyzed with ImageJ program after creating threshold image (Fig. 2b).


(a)


(b)

Fig 2 (a) Scanned image of chile roots using EPSON PERFECTION 3200 PHOTO flat bed scanner and (b) Threshold image of chile roots created by ImageJ program

Results and Discussion

Soil water content and soil temperature

In control θ varied from 0.169 to 0.226 at 0-30 cm depth and from 0.192 to 0.279 at 30-60 cm depth. The lower water content in the upper 0-30 cm depth could be explained by higher moisture loss from surface because of evaporation (Fig. 3). θ values in PRDv treatment varied from 0.169 to 0.218 at 0-30 cm and 0.215 to 0.320 at 30-60 cm depths (Fig. 3). In PRDv subsurface irrigation was applied and upper 33% soil was water stressed. The variation of θ in upper 0-30 cm depth was due to capillary rise or the root water extraction. In PRDc treatment, the trend of water content in both compartments

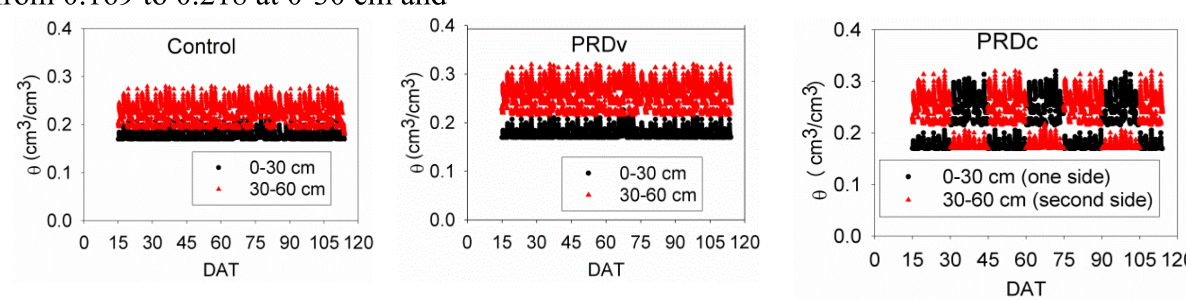

Fig 3. Variation of volumetric water content (θ) at 0-30 and 30-60 cm depths among three treatments i.e., control, PRDv and PRDc during growing period from 15 days after transplant (DAT) to 120 DAT, where date of transplant is April 29, 2013

followed the timing of irrigation (Fig. 3). The variations in soil temperature were similar in all treatments (Fig. 4).

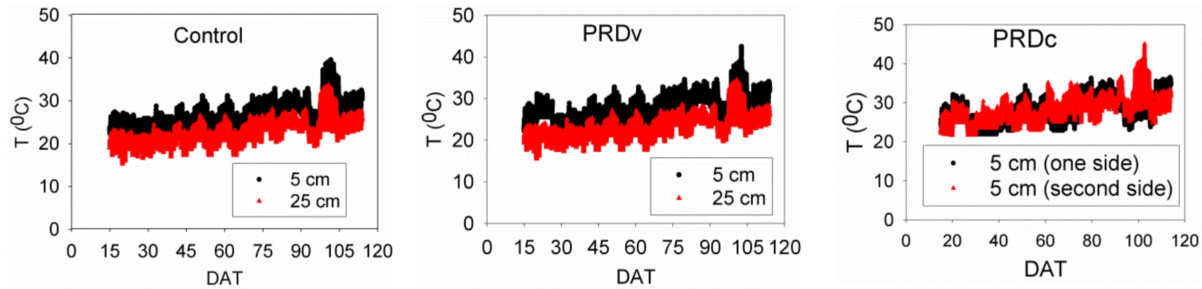

Fig 4. Daily variation of soil temperature (T) at 5 cm and 25 cm depths among three treatments i.e. Control, PRDv and PRDc during growing period from 15 days after transplant (DAT) to 120 DAT, where date of transplant is April 29, 2013

Plant parameters

In PRD treatments, RLD and root lengths were consistently higher than control during all three measurements (Fig. 5). The total root length in PRDv was about 152 to 195% of control while that in the PRDc was about 132 to 160% of the control. In control, roots were mainly concentrated in upper 0-20 cm. depth, while in PRD treatments rooting depths were up to 30 cm. Higher root lengths in PRDv treatment could be because of the low availability of water in the upper 0-20 cm depth and roots grew deeper into the soil profile to extract water from deeper depths. The root growth and root distributions in PRDc treatments were similar in both compartments, but deeper than that in control.

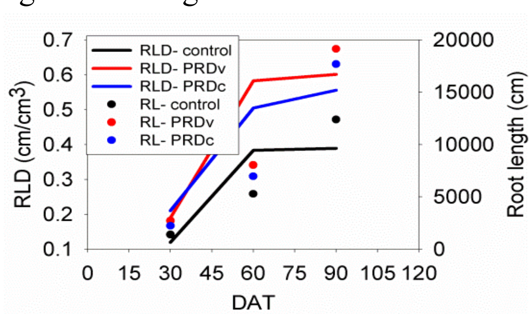

Fig 5. Root length density (RLD) and root length among control, PRDv and PRDc during 30 DAT and 90 DAT (May 14 – July 14, 2013)

Photosynthetic rates, stomatal conductance and transpiration rates remained similar among treatments (Deb et al., 2012) [Fig 6a & b and 7a]. Similar photosynthetic and transpiration rates were also reported for bell pepper by Pallas (1973). In order to sustain peak water demand, plants in both PRD treatments seemed to compensate for water stress in upper 20 cm depth in PRDv and compartment in PRDc by taking up more water from less stressed root zone (zone of higher θ). On accord with the photosynthetic rate and stomatal conductance, the plant height and SWP values among the treatments show only minor temporal variations (Table 1).

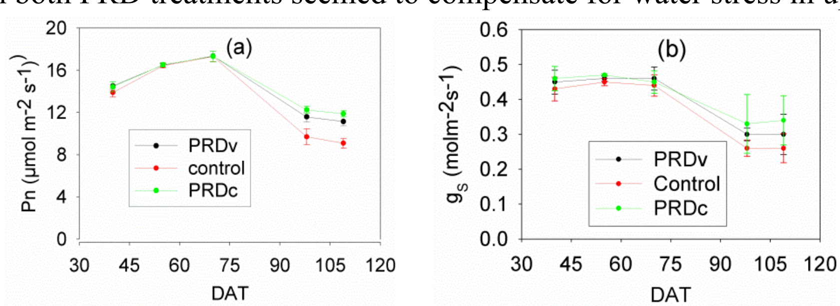

Fig. 6. Photosynthetic rate (Pn) and stomatal conductance (g_S) among all three treatments during growing season from 30 DAT to 120 DAT (May 14 – Aug. 05, 2013)

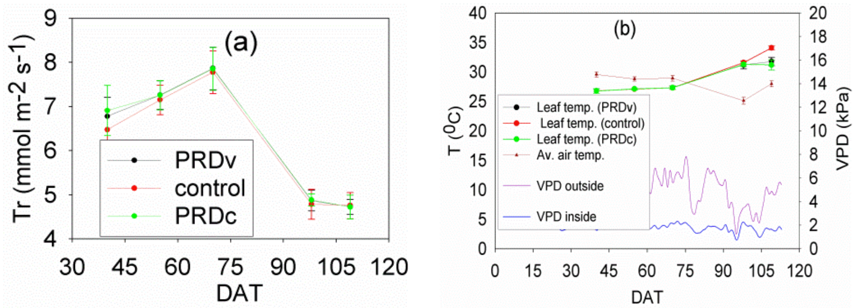

Fig. 7(a) Transpiration rates (Tr) among treatments during growing season from; (b) Average air and leaf temperature for control and PRD treatments, VPD inside and outside the greenhouse during 30 DAT to 120 DAT (May 14 – Aug. 05, 2013)

Table 1. Plant height and stem water potential (SWP) in. Control, PRDv and PRDc

		Days after Transplanting (DAT) on April 14,2013							
Parameters	Treatment	0 Apr. 14	15 Apr. 29	30 May 14	45 May 29	60 June 13	75 June 28	90 July 13	105 July 28
Height (cm)	Control	9.4	12.4	18	26.4	31.6	32.2	39.6	42.9
	PRDv	10	14.2	20	29.2	34.4	36.6	39.3	40.6
	PRDc	10.1	12.4	16.4	24	31.8	33.2	38.0	43.5
Stem water potential (bar)									
(Before irrigation)	Control	-	-	-	-4.88	-	-4.93	-	-4.90
	PRDv	-	-	-	-4.81	-	-4.88	-	-4.82
	PRDc	-	-	-	-4.90	-	-4.89	-	-4.80
(After irrigation)	Control	-	-	-	-1.30	-	-1.31	-	-1.27
	PRDv	-	-	-	-1.27	-	-1.29	-	-1.25
	PRDc	-	-	-	-1.31	-	-1.28	-	-1.20

Conclusions

Partial root zone drying could be used as a water conservation method for chile production in water limited areas. PRD methods can maintain potential photosynthetic and transpiration rate because of deeper roots and more root development in water available zones. In PRDc treatment, the root volume was about 50-50% in both compartments and roots were deeper and RLD were higher in both PRD treatments than control. We conducted this experiment under greenhouse conditions without interference of rainfall, but PRD methods are expected to maintain advantages in field conditions also.

Acknowledgements

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Aeration in Subsurface Drip Irrigation: Academic and Commercial Review of Eight Years of Consistent Crop Yield Increase and Water Use Efficiency

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Abstract: *Plant roots need air for optimal respiration. Without it, soil can become anaerobic, inhibiting plant growth and yield. In addition, crop yield and soil health continue to be major agricultural concerns as we continue to experience regional drought and rationed water delivery. In this presentation we review the physiology of crop production when subjected to oxygenation in large commercial row crop applications. Results from research on aeration treatments which resulted in greater Water Use Efficiency (WUE) as reported by University of Queensland, Australia and significant increase in plant's root mass (40% to 50%) at California State University, Fresno are discussed. We conclude with the findings on significant energy and input savings, from 8 years of operational data using Mazzei AirJection® Irrigation technology to improve WUE, fertilizer inputs and addition of air to the root zone on commercially grown cantaloupes, honeydews, corn, and pepper in the western San Joaquin Valley (SJV), California.*

Keywords. *AirJection® irrigation, Oxygation, Water use efficiency, Nitrogen use efficiency, Return of investment (ROI), and Energy consumption.*

Introduction

This work represents part of our ongoing efforts to evaluate the value of university research and commercial application of AirJection® irrigation for various cropping systems in western San Joaquin Valley (SJV), California.

California is known to be one of the largest and most diverse economies in the United States. Industries such as agriculture, mineral extraction, telecommunications, and computer technology have made California a mixed economy (DWR, 2005). It is estimated that

California's population may reach up to 48 million by 2030, as projected by the California Department of Finance, and by 2050, it may grow to a total of 55 million. With an increasing population, the state's demand for water, either for domestic use, or for agricultural purposes, would invariably enhance the importance of water conservation recycling strategies (DWR, 2005). The present water situation in California has to be seen as a critical need to improve the irrigation practices further but not as a limitation to farming practices.

Sub-surface Drip irrigation (SDI), has been reported to be a very effective way of applying water and nutrients to the crops (e.g. Camp et al., 2000; Ayars et al., 1999). In the San Joaquin Valley (SJV), the leading agricultural production region in California (CDFA, 2003), SDI is a major component of agricultural production systems as farmers continue to compete with municipalities and other industries for decreasing water resources. Over sixty five years ago, Durell (1941) wrote, ‘‘a study of suitable oxygen carriers, which could be applied as fertilizer, and which would release oxygen slowly to the soil during the growing season, may be worthwhile". More recently, through work in other areas, the Mazzei® Corporation has developed high efficiency venturi injectors capable of aerating water with fine air bubbles. The combination of the venturi system with SDI has been patented as AirJection® Irrigation. Researchers in Australia have also adopted this technology and refer to it as "Oxygation" (Bhattarai et al., 2005). The concept of modifying the root zone by injecting air into the subsurface drip irrigation system (SDI) could be an alternative for tillage operations. The hypoxic condition which might be induced due to the alternate wetting and drying using SDI can be avoided by injecting air into the irrigation water supplied through SDI (Bhattarai et al., 2004). When air alone is supplied to SDI system, it emits a vertical stream moving above the emitter outlet directly to the soil surface. As a result, the air moves away from the root zone due to chimney effect (Goorahoo et al., 2001a,b).

The major goal of our research has been to evaluate the technical and economic feasibility of AirJection® Irrigation, as a best management practice for crop production. Ideally, the technology should be applied to and tested on as many crops as possible. Realistically, we plan on assessing the practice on as many vegetable and fruit crops commonly grown in the SJV. In this presentation, we review the basic concepts of AirJection® Irrigation and then describe some of the research our group has conducted to date which has focused on estimating the impact of AirJection® Irrigation on water use efficiency (WUE).

Materials and Methods

Details of the design and theory of operation of the air injection system employed in the research is described above and can be found in Goorahoo et al., (2001a,b). Briefly, the injector/ drip tape assembly operates on the following principle: As water under pressure enters the injector inlet, it is constricted in the injection chamber (throat) and its velocity increases. The increase in velocity through the injection chamber can result in a decrease in pressure below the atmospheric in the chamber. This drop in pressure enables air to be drawn through the suction port and can be entrained into the water stream. As water stream moves towards the injector outlet, its velocity is reduced and the dynamic energy is reconverted into pressure energy. The aerated water from the injector is supplied to the irrigation system. The fluid mixture delivered to the root zone of the plant is best characterized as air/water slurry.

Our research plots were located in Firebaugh (tomatoes) and Mendota (cantaloupe and honeydew melons, sweet corn and peppers) in the SJV, CA. Soils in this region range from sandy loams to clay loams. Generally, crops were grown on 5 feet wide beds and an experimental plot consisted of at least 4 alternating replications of air-injected and no-air treatments (control). Each replicate was made up of seven beds to accommodate the width of the tractor-drawn trailers during harvesting. For example, the honeydew experimental plot comprised of four replicates of each treatment for a total of 56 beds (2 treatments x 4 reps per treatment x 7 beds per rep = 56 beds).

Commercial scale operations included 1497 acres of cantaloupe, melons, corn, and peppers using AirJection. Over the eight year period (2005 – 2012) that equated to a total of 11,978 acres on AirJection irrigated crop production. Yield data were recorded for the various crops, and the energy consumption and return on investment (ROI) were determined using typical costs associated with that for water and power on the farm.

Preliminary Results

In previous work with growers on a commercial test plot basis, Air-jection Irrigation demonstrated bell pepper yield increases of 13 percent and 8 percent for premium and processed bell peppers, respectively. The value of the increased yield was, however, partially offset by increased energy costs. In 2000, a similar study was conducted at the Center for Irrigation Technology (CIT) at California State University (CSU) Fresno on bell peppers (Goorahoo et al. 2001). In that study an increase of 33% in bell pepper count, and a 39% increase in bell pepper weight was noted for the aerated plots versus the plots receiving only water. When the roots were examined, there was a significant difference between the root weight to total plant weight ratios for the aerated plants and the non-aerated plants. The findings from the CSU-Fresno study justified follow-up fieldwork on larger commercial plots. On average, AirJection® Irrigation has resulted in a13-18% yield increase in fresh market tomatoes, cantaloupes, honeydews, broccoli, strawberries and sweet corn (Goorahoo et al., 2008). Similar results have been obtained by a research group at Queensland University in Australia (Bhattarai, et al., 2004, 2005 & 2006). Our most recent work on organic farming systems indicated that AirJection® Irrigation also positively affected photosynthetic and soil respiration rates, stomatal conductance, leaf scale water use efficiency, plant tissue nitrate concentrations, and shoot and root biomass (Reddy, 2008). Figures 1 and 2 are provided as examples of the relative increase in weight and numbers, respectively, for melons grown with AirJection Irrigation.

At the commercial scale, over the eight year period reviewed, Cantaloupes equated to approximately 47% of the total acreage (6,480 acres) and consistently produced the best results with yields anywhere between 12%-34% above the farm average (Figure 3). In the case of sweet corn, the five year average increase was approximately 20 boxes per acre (Figure 4).

The net increase in yield using the same amount of water per acre would be an equivalent cantaloupe production to farming approximately 1000 acres less over 8 year period (Table 1). This crop yield increase would theoretically allow farmers to farm more “crop per drop of water”. While there a slight increase in the energy costs for crops grown with AirJection irrigation compared to those grown with water only (Table 2), the annual return on investment (ROI) was still greater for the air injected crops (Table 3). For example, over the 8 year period the net ROI for the cantaloupe crop was approximately 3.7million U.S. dollars!

Concluding Remarks

Based on the research findings to date, we believe that the use of the Air-jection® Irrigation will show a positive growth effect on other vegetables and fruits, forages, turf, tree crops and other row crops such as cotton. Besides the monetary benefits, the potential ecological benefits associated with AirJection® irrigation include improvements in nitrogen use efficiency, increased activity of soil microbes, and reduced deep drainage of irrigation water. The conservation of scarce water resources will also gain favor for sustainable irrigated agriculture. The increase in yields and potential improvement in soil quality associated with the root zone aeration implies that the adoption of Airjection injection technology could be a sound alternative for growers seeking a tool for increasing crop productivity.

Acknowledgements

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Figure 1: Total number of melons in “air” versus “water” plots.

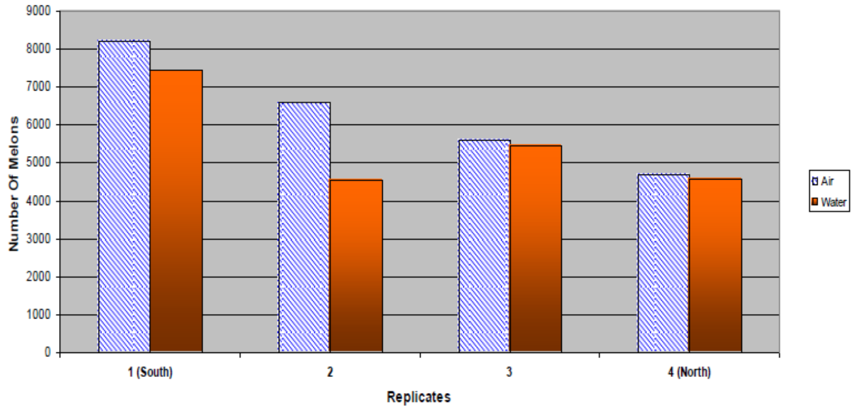

Figure 2: Total weight of melons in “air” versus “water” plots.

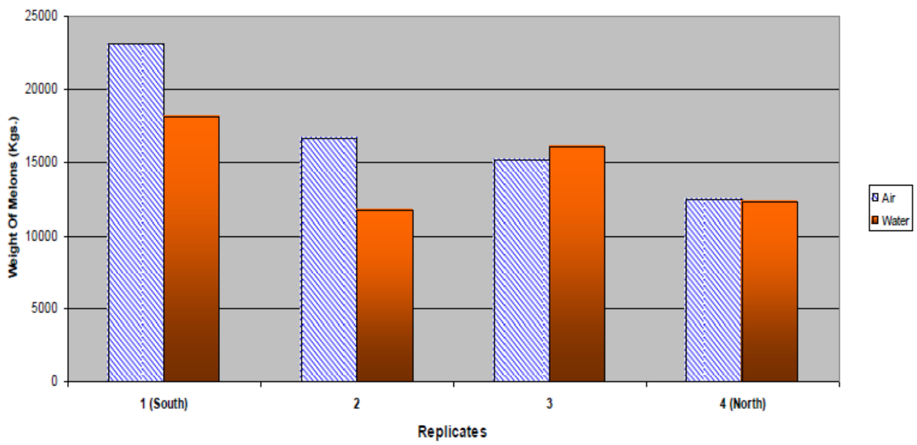

Figure 3: Average yield of melons in “air” versus “water” plots on the commercial farm.

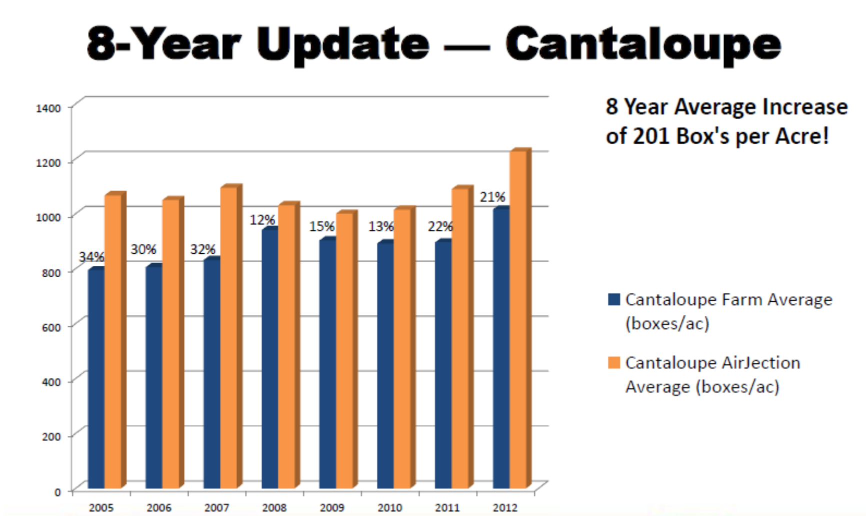

Figure 4: Average sweet corn yield in "air" versus "water" plots on the commercial farm.

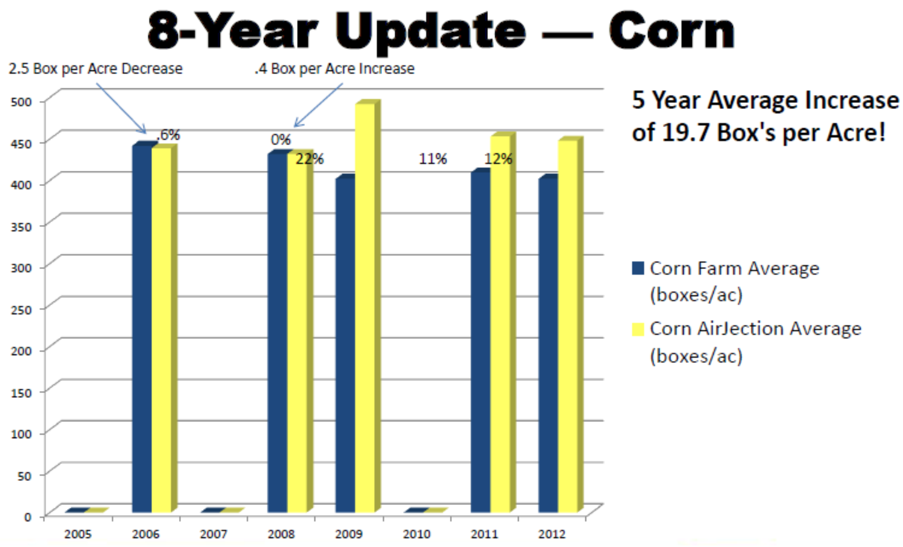

Table 1: Increases in crop production as a result of AirJection Irrigation.

Crop	Total AirJection® Acreage	Total of AirJection® Field Boxes	"Total Boxes" for equivalent AirJection® Acreage	Average per acre increase in boxes	Total Box Increase over Farm Average
Cantaloupes	6,480	6,891,383	5,590,794	201	**1,300,590**
Corn	3,416	1,513,770	1,446,499	20	**67,271**
Honeydews	1,320	2,063,656	1,855,783	134	**176,305**
Bell Peppers	460	936,365	768,581	371	**170,290**

Table 2: Summary of energy consumption for crop production on the commercial farm.

Crop	Total AirJection® Acreage	Total of AirJection® Field Boxes	AirJection Energy Cost Per Box[1]	"Total Boxes" for equivalent AirJection® Acreage	Non-AirJection equivalent energy cost per Box[1]	Average per acre increase in boxes	Total Box Increase over Farm Average
Cantaloupes	6,480	6,891,383	$0.02	5,590,794	$0.012	201	1,300,590
Bell Peppers	460	936,365	$0.010	768,581	$0.006	371	170,290

[1]Assuming 75% pump efficiency, $.11/KwH energy cost, 15 psi pressure increase for AirJection Irrigation @ same flow rate, and 2 acre-feet of water needed for 1 acre of Cantaloupes and Bell Peppers during a normal growing season. Reference www.icalcul8.com/pump_power.php

Table 3: Return of Investment for Cantaloupe grown with AirJection on the commercial farm.

AirJection® Acreage	Approximate number of AirJection® Injectors per acre	Approximate Installation Cost	Total Installation Costs of AirJection® Injectors	8 Year Weighted Installation Costs of AirJection® Injectors on Cantaloupes	Additional AirJection Energy Cost Per Box
1497	5.5	$140/acre	$209,580	$111,077	$0.0064

Total of AirJection® Field Boxes	Total Energy Cost for 6480 Acres	Average per acre increase in Cantaloupe boxes	Total Additional Box Increase over Farm Average	Conservative Net Price per Box	8-Year Return on Investment	8-Year Net Return on Investment
6,891,383	$67,327	201	1,300,590	$3.00	**$3,901,770**	**$3,723,366**

Review of two decades of progress in the development of successful drip irrigation for onions

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Abstract

*The irrigation needs of long day onion (*Allium cepa*) have been extensively studied at Ontario, Oregon, over the past 22 years. Drip irrigation has compared favorably with furrow and sprinkler irrigation systems. Onions were found to have very narrow soil moisture requirements. Drier soil than optima led to yield loss and wetter soil promoted bulb decomposition. Short term water stress at the three- to six-leaf stages of plant growth promoted multiple centers in long day onion varieties. Irrigation was successfully scheduled using soil water tension or evapotranspiration. Nitrogen fertilization and plant populations have been optimized. Drip system design must carefully consider the hydraulic conductivity of the soil in the placement of tape and onion rows since the soil moisture must wick over from the drip tape to the onion plant. The drip irrigation system design uniformity, operation, and maintenance are essential given onion's low tolerance to water stress.*

Key words: *Allium cepa,* irrigation criteria, soil water tension, drip system design

Introduction

Onions (*Allium cepa* L.) are more sensitive to water stress compared to many other crops. Onion leaves operate at low turgor pressure compared to other plants and stomata close at relatively low leaf water potentials (Millar et al., 1971). Gale et al. (1967) tested the response of bean, cotton, and onion plants to chloride salinity in the root medium and found that onions had the lowest capacity to adjust leaf turgor pressure in response to changes in salinity. In agreement with these physiological studies are studies that found that the soil water tension (SWT) at which onions should be maintained for maximum yields is close to or wetter than field capacity (10 to 30 cb). Coelho et al. (1996) describe onion yield responses to a SWT of 8.5 cb, and Abreu et al. (1980) report a yield response to a SWT of 10 cb. Klar et al. (1976) report onion yields to be highest with the lowest SWT tested (15 cb). Shock et al. (1998b) show onion yields to be highest with the lowest SWT tested (12.5 cb).

Onions have shallow root systems. Drinkwater and Janes (1955) found most onion roots to be located in the top 0.18 m of soil. Greenwood et al. (1982) found that 90% of onion roots are located in the upper 0.18 m of soil. Thorup-Kristensen (2006) found onions to have a final rooting depth of 0.3m. Onions, being sensitive to water stress and having shallow root systems, need frequent irrigations to maintain high soil moisture to produce high yields (Al-Jamal et al., 2000; Bucks et al., 1981; Chung, 1989; de Santa Olalla, 1994; Ells et al., 1993; Hanson and May, 2004; Hegde, 1986; Jones and Johnson, 1958; Kadayifci et al., 2005; Koriem et al., 1994; Nassar and Waly, 1977; Rajput and Patel, 2006; Rana and Sharma, 1994; Shock et al. 1998b, 2000b). Other studies have found that onion yields will respond to irrigation regimes applying more than full onion evapotranspiration (Al-Jammal et al., 2000; de Santa Olalla et al., 1994) or more than full pan evaporation (Kumar et al., 2007).

The negative environmental consequences of furrow irrigation can be exacerbated by the frequent irrigations and high soil moisture required by onions. With furrow irrigation, large amounts of water are unavoidably applied, leading to leaching and runoff. Halvorson et al. (2002) found N fertilizer movement to a 180 cm depth below onion with conservatively managed furrow irrigation. Feibert et al. (1995) found that N was leached from the soil profile when onions were furrow irrigated, but not when onions were drip or sprinkler irrigated. Drip irrigation can reduce the negative environmental consequences of irrigation by applying less total water and smaller amounts of water at a higher frequency than with furrow irrigation. Onion production with furrow irrigation is increasingly being replaced by drip irrigation.

The Malheur Experiment Station compared furrow, drip, and sprinkler irrigation for onion production in 1992-1994 in an attempt to find an irrigation method where it would be possible to grow a successful crop without leaching nitrogen fertilizer below the root zone. Based on the preliminary encouraging results, we initiated research in 1995 to improve the feasibility of commercial onion production under drip irrigation.

The Malheur Experiment Station is located in the Snake River valley on the border of southwest Idaho and southeastern Oregon, more commonly called Treasure Valley. The Treasure Valley annually produces 22,000 acres of Sweet Spanish onions classified as long day and medium-to-long storage (Shock et al., 2000a). Onions are marketed starting at harvest in August and out of storage through April, so maintaining bulb quality during storage is indispensable. Onion growers in the Treasure Valley target the larger onion size classes (jumbo, colossal, and super colossal) because of price premiums for the larger bulbs (Shock et al., 2005b).

Procedures

This paper summarizes research on drip irrigation of onion with emphasis on the studies conducted at the Malheur Experiment Station in Ontario, OR. A complete discussion of procedures for each study is omitted here and can be accessed using the citations. The following general procedures were used in all the Oregon studies unless otherwise stated.

The soil in all studies was an Owyhee silt loam (coarse-silty, mixed, mesic, Xerollic Camborthid). Onions were generally grown in a 5-year crop rotation with wheat, sugar beets, corn, and wheat preceding the onion crop. In the fall preceding the trials, the fields were plowed, roller harrowed twice, fumigated with dichloropropene and chloropicrin (77.9% 1,3-dichloropropene + 16.5% chloropicrin, sold as Telone C-17; Dow Agrosciences, Indianapolis, Ind.) at 225 $L•ha^{-1}$ and bedded. Onions were planted at 370,000 seeds/ha in two double rows per 1.1-m bed in mid-March. The onion double rows were spaced 0.56 m apart. The single rows within the double row were spaced 76 mm apart. One drip tape was installed at 0.08 – 0.10 m depth in each bed between the two double rows. The drip tape had emitters spaced 30 cm apart and an emitter flow rate of 0.55 $L•h^{-1}$.

The irrigations were automatically controlled by a datalogger (CR10, Campbell Scientific, Logan, Utah) connected to solenoid valves. Irrigation decisions were made multiple times per day by the datalogger and were based on soil water tension (SWT). Soil water tension was measured with granular matrix sensors (GMS, Watermark Soil Moisture Sensors Model 200SS, Irrometer Co. Inc., Riverside, Calif.) installed at 0.2 m depth in the center of the onion double row. Sensors had been previously calibrated to SWT (Shock et al. 1998a; Shock, 2003) and tensiometers were used in 1992 and 2005 to confirm the validity of watermark calibration. The GMS were connected to the datalogger using multiplexers (AM 410 multiplexer, Campbell Scientific). The datalogger read the sensors and recorded the SWT every hour.

Onion evapotranspiration (ET_c) was calculated by the Pacific Northwest Cooperative Agricultural Weather Network (AgriMet, U.S. Bureau of Reclamation, Boise, Idaho) from data collected at the Malheur Experiment Station by an AgriMet weather station using crop coefficients and a modified Penman equation (Wright 1982). Pan evaporation was measured using a class A pan at a NOAA weather station immediately adjacent to the AgriMet weather station.

In early September, the onions were undercut with a rod weeder to field cure for about a week. After curing, the onions were topped, bagged and placed into storage. The storage shed was managed to maintain air temperature as close as possible to 1°C.

Growers in the Treasure Valley market onions directly from the field and after up to 7 months of storage. For the data for drip-irrigated onion trials to be representative of the local marketing conditions, the onions were stored for approximately 2 to 3 months before grading each year. Onion yield, grade, and water use efficiency were all based on onion yield out of storage. The onions were graded in early December each year. Bulbs were separated according to quality: bulbs without blemishes (No. 1s), split bulbs (No. 2s), and diseased bulbs. The No. 1 bulbs were graded according to diameter: small (< 57 mm), medium (57 to 76 mm), jumbo (76 to 102 mm), colossal (102 to 108 mm), and super colossal (>108 mm). Marketable onions were considered perfect bulbs in the medium, jumbo, colossal, and super colossal size classes.

After grading, 50 bulbs ranging in diameter from 89 to 108 mm from each plot were rated for single centers. The onions were cut equatorially through the bulb middle and, if multiple centered, the long axis of the inside diameter of the first single ring was measured. These multiple-centered onions were ranked according to the diameter of the first single ring: small (< 38 mm), medium (38 to 57 mm), and large (> 57 mm). Onions were considered “functionally single centered” for processing if they were single centered or had a small multiple center.

Results and Discussion

Optimum SWT

Research was initiated in 1997 to determine the optimum SWT for scheduling irrigations for drip irrigated onion (Shock et al., 2000a). Onion was submitted to five SWT treatments (10, 20, 30, 50, and 70 cb) using subsurface drip irrigation in 1997 and 1998 (Fig. 1). The SWT in each plot was maintained relatively constant by automatically applying 1.5 mm of water up to 8 times a day as needed based on SWT readings.

The high frequency, short irrigations possible with the automated system were able to maintain the SWT at 0.2 m depth relatively constant for the 10 and 20 cb treatments (Fig. 1). As the treatments became drier than 20 cb the oscillations in SWT increased. The 10 cb treatment applied more water than onion ET_c for the season and the 20 cb treatment applied close to the same amount of water as onion ET_c for the season (Fig. 2). The drier treatments applied less water than onion ET_c for the season.

In 1997, onion total yield and size were highest with the wettest treatment (10 cb). However, marketable yield was maximized at a SWT of 21 cb due to an increase in decomposition in storage with wetter treatments (Fig. 3). Onion profits were maximized by a SWT of 17 cb. In 1998, decomposition in storage was not influenced by treatment, and onion total yield, size, marketable yield (Fig. 3), and profits were maximized by the wettest treatment of 10 cb. Considering the higher nitrate leaching potential with a SWT wetter than 20 cb and the difficulty of predicting the storage quality of the crop, the use of a SWT closer to 17 cb for drip irrigated onion is suggested.

These results are similar to those of Shock et al. (1998b), who found that, with furrow-irrigated long-day onions at the Malheur Experiment Station, the optimum SWT at 0.2 m depth as an irrigation threshold ranged from the highest tested level (12.5 cb) down to 27 cb, depending on the level of storage decomposition each year. However, with automated, high frequency, drip irrigation, the optimum SWT could be higher than with furrow irrigation. With furrow irrigation, large oscillations of SWT are difficult to avoid and could lead to longer periods of excessively wet soil, which could promote disease. Research with short-day onions has also shown similar results. Coelho et al. (1996) reported a yield response to a threshold of 8.5 cb, and Abreu et al. (1980) reported a yield response to a threshold of 10 cb. Klar et al. (1976) report onion yields to be highest with the lowest threshold tested (15 cb). However, comparison of the present study with others using less frequent irrigations (Abreu et al., 1980; Klar et al., 1976; Shock et al., 1998b) is complicated because of the different irrigation frequencies, environments and cultivars. In addition, all of the studies with short-day onions evaluated yields out of the field and none considered the possibility of bulb decomposition in storage or variable decomposition in storage as a function of irrigation treatment. Decomposition can be increased by a low SWT irrigation criterion (Shock et al., 1998b, 2000a).

Reduction of season-end irrigation threshold for reduction of storage decomposition

In conjunction with the 1997 and 1998 soil water tension trials, the effect of reducing the SWT in the last third of the growing season on onion storage decomposition was also tested (Shock et al., 2000b). The soil water tension at which automated irrigations were started was increased from 20 cb to 30, 50, or 70 cb after July 15. Any increase of the SWT from 20 cb did not reduce storage decomposition, but reduced colossal onion yield in 1997 and marketable and total yield in 1998. These results are consistent with van Eeden and Myburgh (1971) and Dragland (1974) who found water stress in the latter part of the season reduced onion yields, but did not reduce storage decomposition.

N fertilization and plant population

In 1999, 2001, and 2002, research to determine N fertilization requirements and plant population for drip irrigated onion was conducted (Shock et al., 2004). Drip irrigation can reduce leaching, because a smaller amount of water can be applied at each irrigation, avoiding a large oscillation in soil moisture and saturation of the soil profile that occurs with furrow irrigation. Lower N fertilizer requirements would be expected with drip irrigation. With a new onion size category being used for marketing (super colossal) and the increased revenue accrued from larger bulbs, a reexamination of the relationship between plant population and bulb size and yield became necessary.

Each year, onions were grown on fields that had been cropped with wheat for 4 years. Each wheat crop received moderate N fertilization (168 kg/ha). Onions were drip irrigated automatically using a soil water tension of 20 cb to initiate irrigations every three hours if necessary. The irrigation intensity was 1.6 mm of water/ irrigation. Onions were subjected to a combination of seven N rates (0, 56, 112, 168, 224, 280, and 336 kg/ha) and four plant populations (185, 250, 300, and 370 thousand plants/ha). The nitrogen for each treatment was split into 5 equal amounts and applied through the drip tape every 10 days from mid-May to early July. Soil was sampled before and after the onion crop. Irrigation water N content was determined and onion N uptake (bulbs and tops) was measured for each treatment.

Onion marketable yield increased and bulb diameter decreased with increasing plant population (Fig. 4). Within the range of plant populations tested, gross returns were not always responsive to plant population. Returns were increased by the increase in marketable yield obtained by higher plant population, but higher plant populations also reduced the production of the largest size bulbs which had the highest value per weight. In 1999, when super colossal bulbs were not measured, gross returns increased with increasing plant population and reached a maximum at 371,000 plants/ha. In 2000, the plant population maximizing gross returns was 266,000 plants/ha. In 2001, gross returns were not responsive to the range of plant populations tested. The plant populations maximizing gross returns in this study were substantially lower than the range of 309,000 to 514,000 plants/ha found to maximize gross returns previously (Shock et al., 1990), when colossal and super colossal bulbs were neither measured nor as important in onion marketing.

Onion yield and grade were not responsive to N fertilizer rate or the interaction of N fertilizer rate with plant population. Preplant soil available N, N mineralization, and N in irrigation water all contributed N to the crop (Fig. 5). Previous research at the Malheur Experiment Station investigating N rates for furrow irrigated onions found no response of onion yield to N fertilizer in 3 out of 4 site years (Shock et al., 1991, Miller et al., 1992). Low N needs for drip-irrigated onion are consistent with full size commercial demonstrations (Shock and Klauzer, 2003). The N mineralization rates in this study are within the range determined for Treasure Valley soils (Carter et al., 1975; Stieber et al., 1995; Shock et al., 1998c).

Despite the carefully managed irrigations, leaching of nitrate and or volatile N losses from the crop root zone occurred in 1999 and 2001 for the higher N rates. Other research, with highly efficient drip irrigation systems, has also found that some leaching below the crop root zone will occur when irrigating for maximum yield. In New Mexico on a sandy loam, with one drip tape per bed and irrigations on alternate days, deep percolation occurred when the irrigation system was operated for maximum onion yield and to keep the full bed surface wet (Al-Jamal et al., 2001). For cauliflower (*Brassica oleracea* L.) (Thompson et al., 2000), collard (*Brassica oleracea* L.), mustard (*Brassica juncea* L.), and spinach (*Spinacea oleracea*, L.) (Thompson and Doerge, 1995b), lettuce (*Lactuca sativa* L.)(Thompson and Doerge, 1995a), and watermelon (*Citrullus lanatus* Thumb.)(Pier and Doerge, 1995) drip irrigated daily on a sandy loam in Arizona, irrigating for maximum yield was just below or at the SWT that resulted in N leaching. Sweet corn (*Zea mays* L.) grown on sandy loam in Israel with one tape per row and irrigated daily using Et_c replacement, resulted in drainage below the crop root zone even with 0.25 L•h^{-1} emitters (Assouline et al., 2002).

Irrigation intensity and emitter flow rate

The automated irrigation system used for research at the Malheur Experiment Station used an irrigation intensity of 1.5 mm per irrigation with an irrigation frequency of up to 8 times per day, which would be impractical on a commercial scale. The emitters had a flow rate of 0.5 L•h^{-1}, but lower flow emitters have been advocated as a means of improving irrigation uniformity. In 2002 and 2003, research was conducted to determine onion response to drip irrigation intensity and emitter flow rate (Shock et al., 2005a). Onions were submitted to eight treatments as a combination of four irrigation intensities (1.6, 3.2, 6.4, and 12.7 mm of water per irrigation) and two drip tape emitter flow rates (0.5 and 0.25 L•h^{-1}). Onions in each plot were submitted to one irrigation intensity and one emitter flow rate. Each plot was irrigated independently and automatically when the SWT reached 20 cb. Irrigation intensities of 12.7 mm per irrigation slightly increased onion yield and grade above the irrigation intensity of 1.6 mm per irrigation. An irrigation intensity of 12.7 mm did not result in an increase in water applied (Fig. 6) nor in any significant difference in average soil water tension (Fig. 7). The 12.7 mm irrigation intensity corresponded to an irrigation frequency of every 1 to 2 d. Lowering the emitter flow rate from the currently used of 0.5 L•h^{-1} to 0.25 L•h^{-1}, resulted in slightly lower onion yield and grade.

Other studies investigating irrigation intensity and emitter flow rate are not comparable, because of varying factors. The irrigation frequencies tested were much lower than ours or the onion production and marketing conditions were different from our studies (Bucks et al., 1981; Ellis et al., 1986; Kannan and Mohamed, 2001). Some studies were done with processing onions (Hanson et al., 2003), or onions marketed at much smaller size classes. In other studies, the irrigations were not automated and scheduling was not based on SWT feedback (Assouline et al., 2002).

Response of onion single centeredness to short duration water stress

Single centeredness has become an important onion attribute for marketing due to the use of onions in food products such as onion rings. Onion single centeredness is dependent on cultivar (Shock et al., 2005b), and is also influenced by growing conditions. Trials in 2003, 2004, and 2005 tested the effects of early season short duration water stress on onion single centeredness (Shock et al., 2007). The effects of the short duration water stress were also evaluated on onion yield, grade, and translucent scale. Translucent scale is a physiological disorder that might be influenced by water stress (Werner and Harris, 1965). Onions were drip irrigated automatically at a SWT of 20 cb and an irrigation intensity of 6.4 mm of water per irrigation. Onions in each treatment were stressed once at either the 2-leaf, 4-leaf, early 6-leaf, late 6-leaf, or 8 leaf stage and compared to a minimally stressed check (Fig. 8). Onions were stressed by interrupting irrigations until the SWT at 0.2 m depth reached 60 cb, at which time the irrigations were resumed. Onion single centeredness was reduced by short duration water stress in 2003 and 2005 (Fig. 9). Onions were sensitive to the formation of multiple centers with water stress at the 2-leaf to late 6-leaf stages. The 2004 growing season was characterized by cool, moist conditions and water stress did not affect single centeredness. Among all treatments and years, marketable yield was only reduced in 2005 with stress at the 4-leaf and 8-leaf stages. The incidence of translucent scale was very low each year and not related to early season water stress.

Our results are in agreement with Pelter et al. (2004) who found that water stress at the 3-leaf stage reduced single centeredness. However, contrary to our results, in the Pelter et al. (2004) study the reductions in single centeredness with stress at the 5-leaf stage were not significantly different from the check. Pelter et al. (2004) found that total yield was reduced by all stress treatments and colossal yield was reduced by stress at the 5, 7, and 9-leaf stages, contrary to our results. Our results showed yield reductions only in 2005 for total marketable yield from stress at the 8-leaf stage and for yield of combined jumbo, colossal, and super colossal bulbs from stress at the 4-leaf and 8-leaf stages. The yield reductions in the Pelter et al. (2004) study may be related to the more intense and longer water stress than in our study. The more intense water stress was due to the consistently higher SWT that the stressed plots were allowed to reach (70 cb) than in our study, and also due to their delays in restarting irrigation at the end of the stress treatments. Several of the stress treatments in the Pelter et al. (2004) study had SWT reaching or exceeding 100 cb for 10 days or more. The stress levels used in the Pelter et al. (2004) study are less likely to occur in commercial onion fields.

Conclusions of research in eastern Oregon

On silt loam soil, the optimum soil water tension for maximizing yield of long day onions after storage is 25 cb with furrow irrigation and 17 cb with drip irrigation.

Increasing the soil water tension in the latter part of the season did not reduce storage decomposition, but reduced bulb yield and size. Short duration water stress coinciding with warmer weather early in the growing season (Shock et al. 2007) was associated with yield reductions.

Within the range of plant populations tested (185,000 to 370,000 plants/ha), marketable yield increased and bulb size decreased with increasing plant population. Using gross returns as a criterion for determining the ideal plant population, gross returns were maximized by plant populations in the range from 266,000 plants/ha to 371,000 plants/ha, depending on the maximum bulb size desired and the prevailing market price structure.

Onions grown on silt loam in eastern Oregon previously cropped for 4 consecutive years of moderately fertilized wheat showed no response to N fertilizer under carefully managed drip irrigation. Preplant soil available N, N mineralization, and N in irrigation water all contributed N to the crop. Onion N uptake was maximized with no added N fertilizer and there was no difference in uptake between N treatments. Onion N uptake averaged 239 $kg \cdot ha^{-1}$ over all N rates and over three years.

When onions grown on silt loam were drip irrigated automatically to maintain a soil water tension of 20 cb, irrigation intensities of less than 13 mm of water per irrigation did not increase yield or size and did not reduce the total amount of water applied. An irrigation intensity of 13 mm per irrigation resulted in an irrigation frequency of every 1 to 2 days.

Onions were sensitive to formation of multiple centers with short-duration water stress (allowing SWT to reach 60 cb from 20 cb once during the season) at the four-leaf to six-leaf stages. The incidence of translucent scale was very low and was not affected by early season short-duration water stress.

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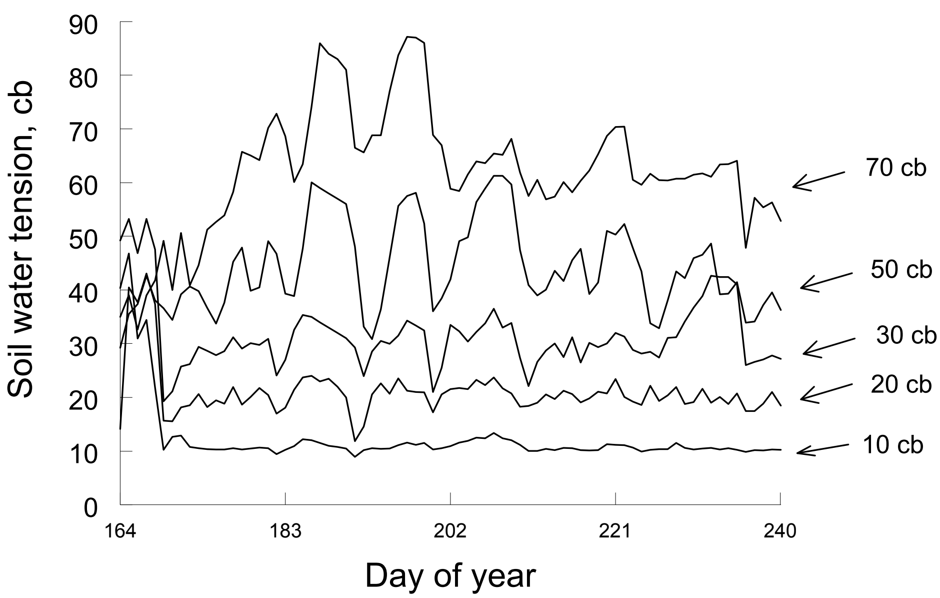

Fig. 1. Soil water tension over time for onions drip-irrigated automatically at five soil water tensions in 1997 (Shock et al., 2000a).

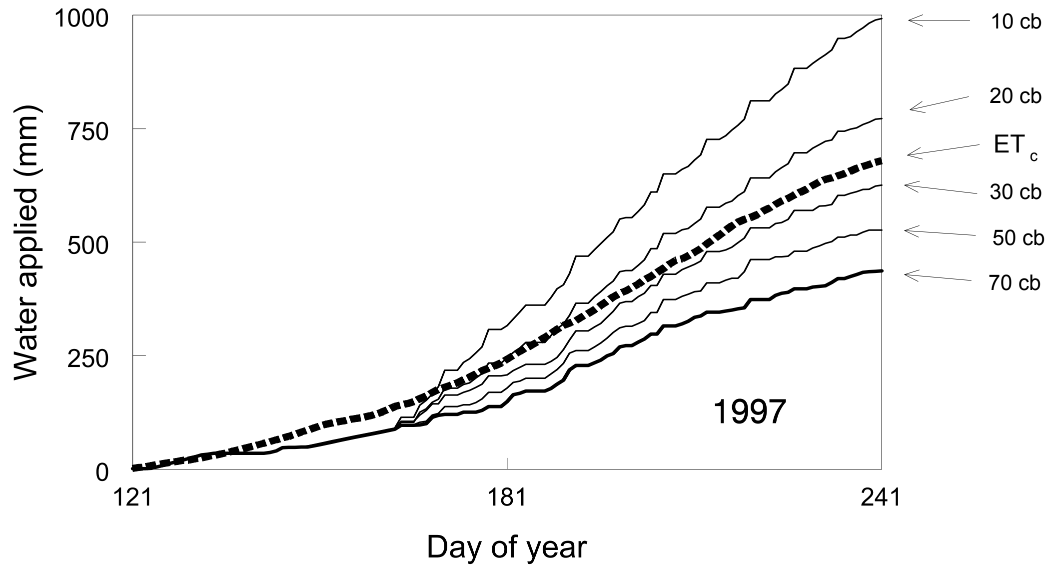

Fig. 2. Water applied over time and ET_c for onions drip-irrigated automatically at five soil water tensions in 1997 (Shock et al., 2000a).

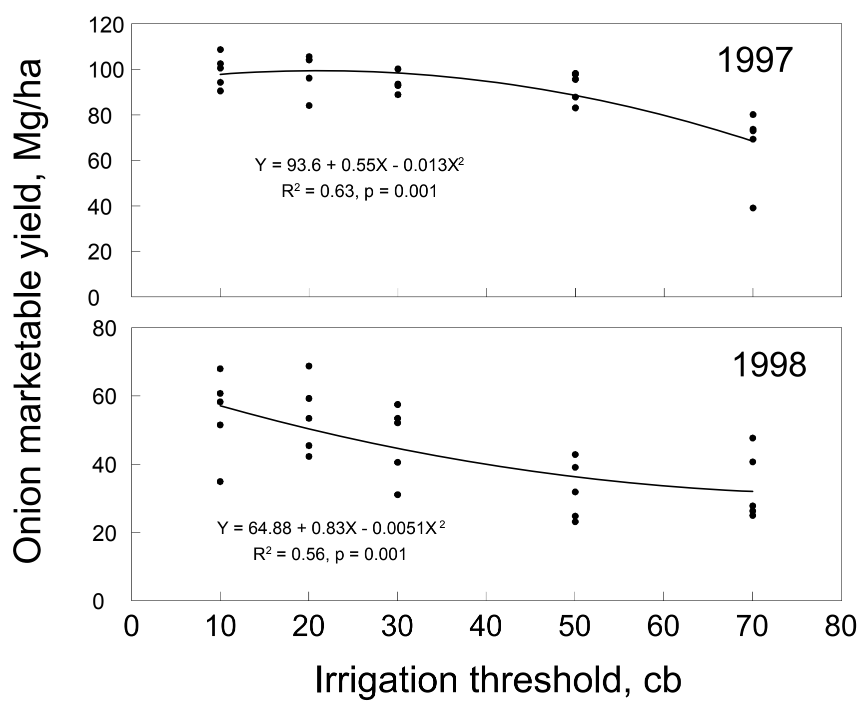

Fig. 3. Marketable yield for onions drip-irrigated automatically at five soil water tensions (Shock et al., 2000a).

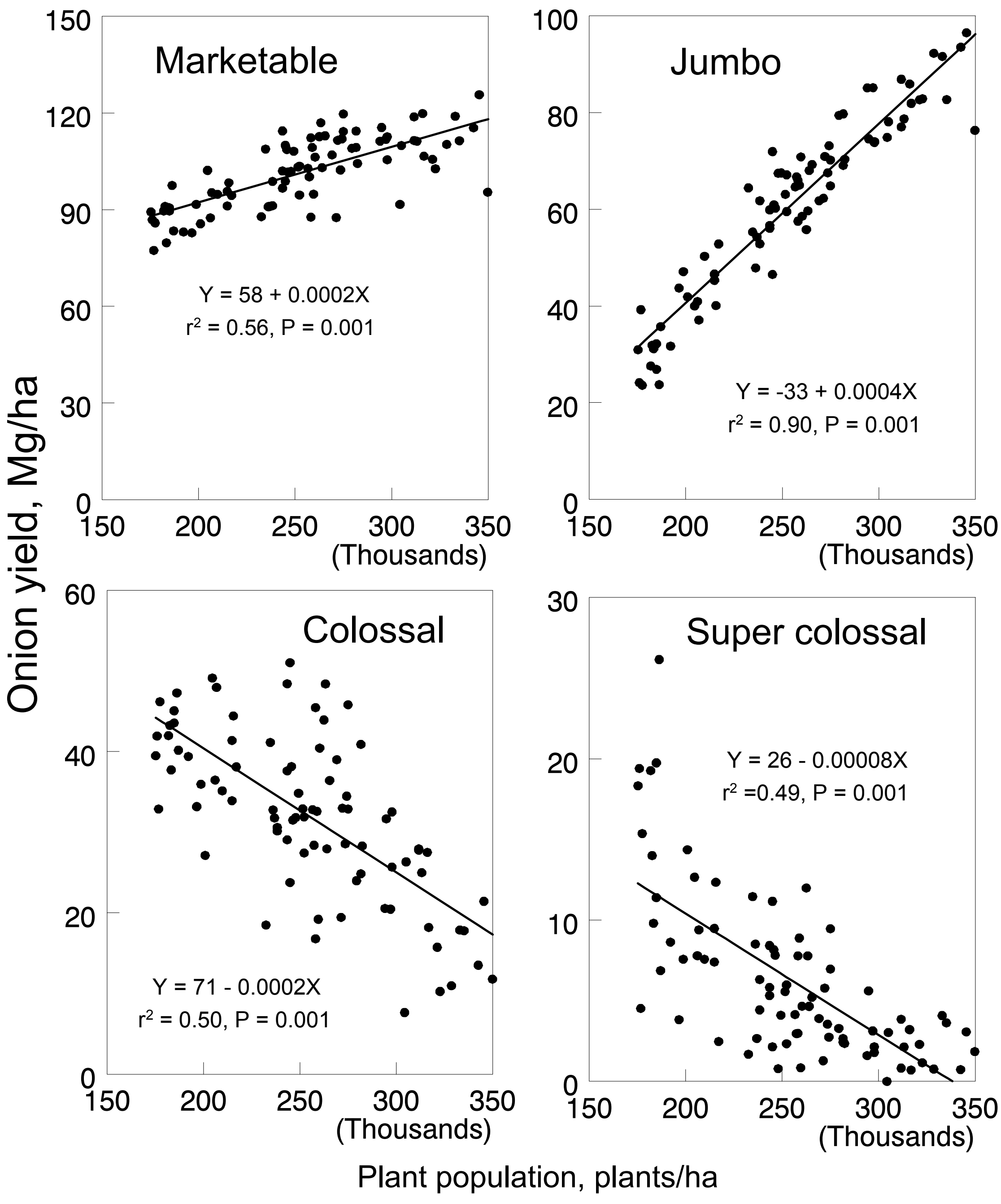

Fig. 4. Onion yield response to plant population in 2001 over seven N rates (Shock et al., 2004).

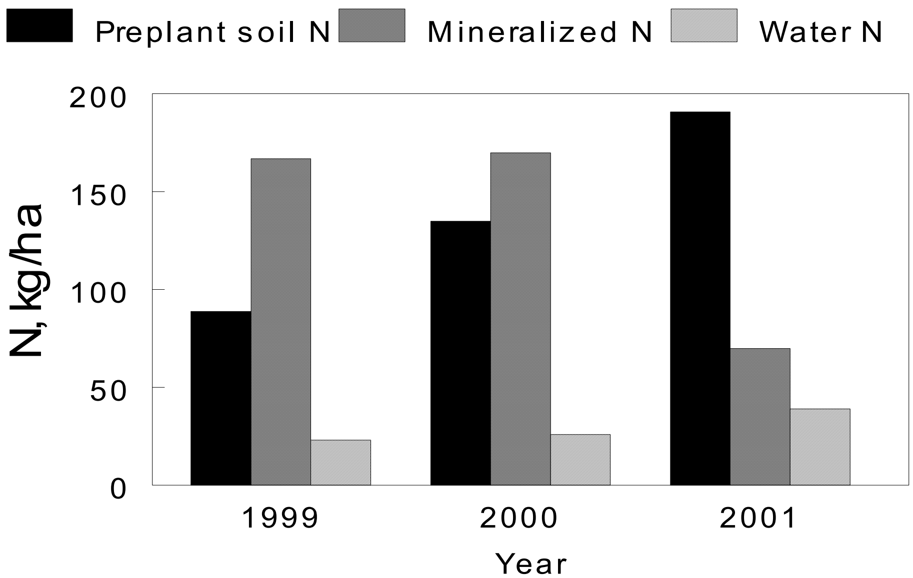

Fig. 5. Natural sources of N available to drip-irrigated onion (Shock et al., 2004).

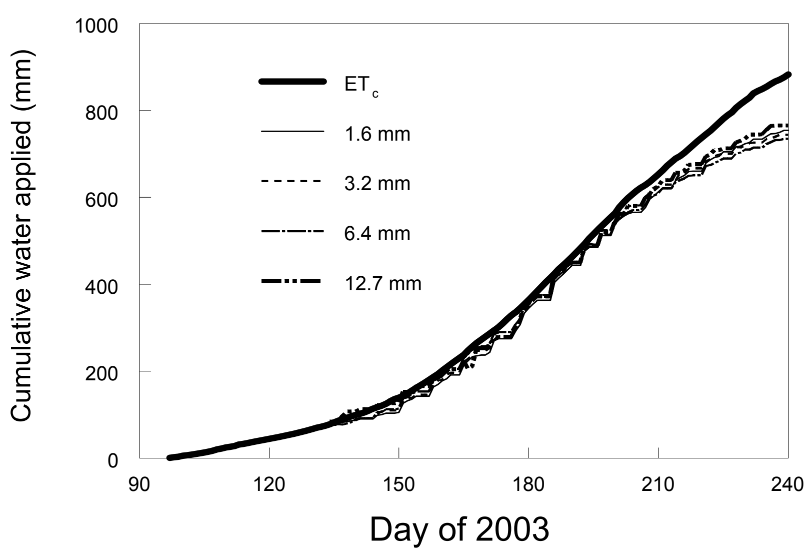

Fig. 6. Onion evapotranspiration (ET_c) and total water applied (includes precipitation) over time for four irrigation intensities (amount of water applied per irrigation) with 0.5 $L•h^{-1}$ emitter in 2003 (Shock et al., 2005a).

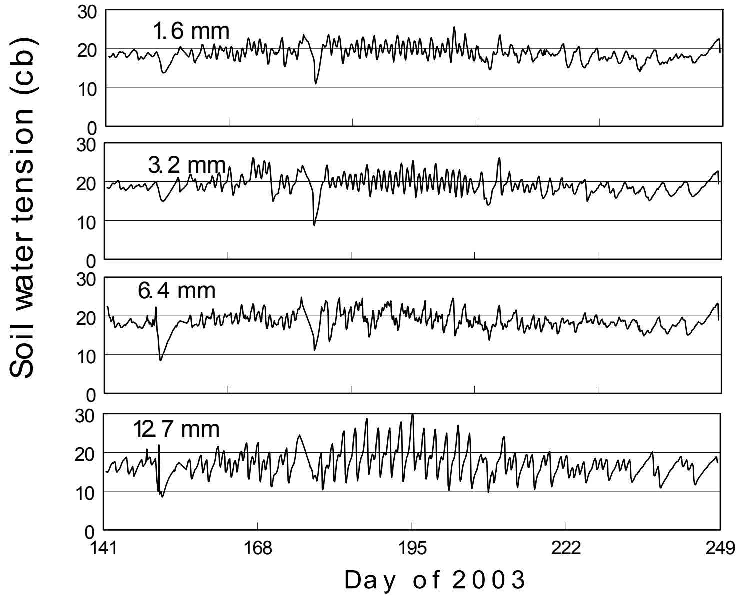

Fig. 7. Soil water tension at 0.2 m depth over time for onions drip irrigated at four intensities with an emitter flow rate of 0.5 L•h^{-1} (Shock et al., 2005a).

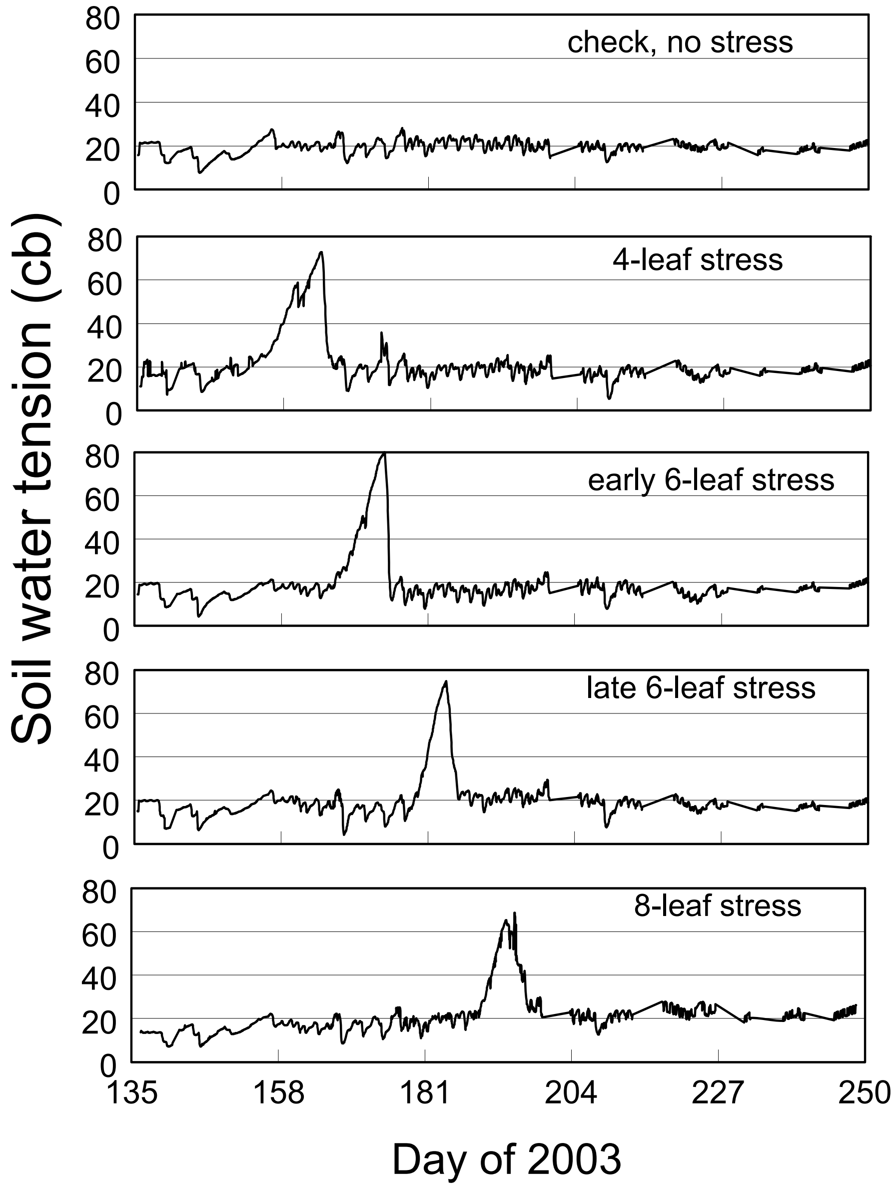

Fig. 8. Soil water tension for onions drip irrigated automatically at 20 cb and submitted to short-duration water stress (Shock et al., 2007).

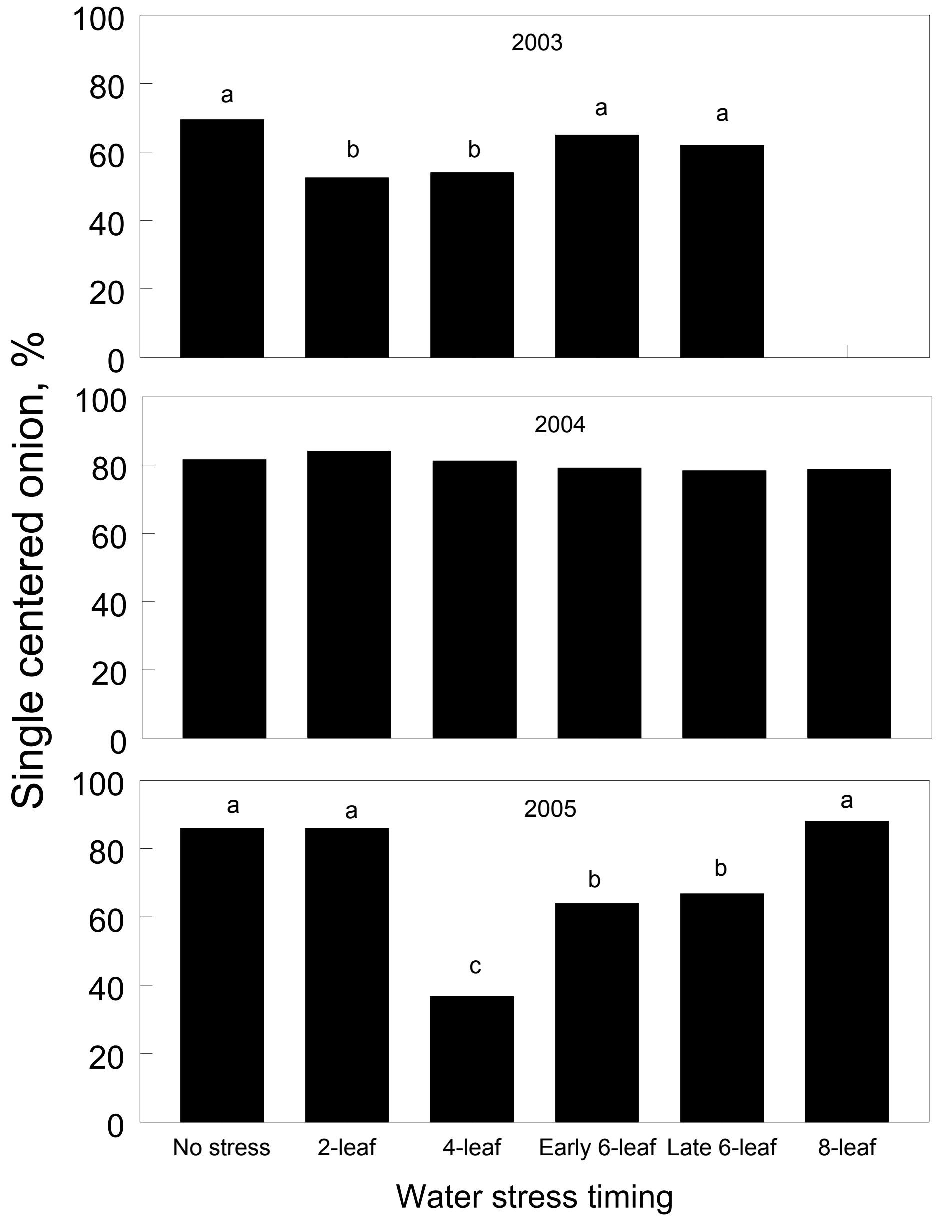

Fig. 9. Onion single centeredness response to short duration water stress at five growth stages. Columns followed by different letters are significantly different according to Fisher's protected least significant difference test at 0.05 probability level (Shock et al., 2007).

Agricultural Irrigation and Water Conservation in Texas

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Abstract. *According to the 2012 State Water Plan, irrigated agriculture is the largest water use sector in Texas. Increased municipal demands following tremendous urban population growth are projected to surpass the agricultural sector within the next 50 years. Conservation of agricultural irrigation water is expected to create 17% of water management strategies needed to meet this growth.*

The Texas Water Development Board provides financial assistance and educational outreach for the conservation of water across all sectors. Our grant funded Agricultural Water Conservation Demonstration Initiative projects in the High Plains and Lower Rio Grande Valley showcase best management practices and enable the transfer of proven, efficient, and innovative irrigation technologies to area producers. The threat of continual drought conditions highlights the importance of water conservation throughout the state, and maximizing irrigation efficiency while maintaining agricultural productivity is essential to ensuring the viability of water resources in Texas now and into the future.

Keywords. water conservation, agricultural irrigation, Texas, water use efficiency, regional water planning, best management practices.

The Texas Water Development Board

The Texas Water Development Board (TWDB) is the state's water planning and water project financing agency. The TWDB's main responsibilities are threefold: collecting and disseminating water-related data; assisting with regional water planning and preparing the state water plan for the development of the state's water resources; and administering cost-effective financial programs for constructing water supply, wastewater treatment, flood control, and agricultural water conservation projects. In response to the drought of the 1950s and in recognition of the need to plan for the future, the legislature created the TWDB to develop water supplies and prepare plans to meet the state's future water needs. Since 1957, the TWDB has been charged with addressing the state's water needs. The TWDB has both leadership and support roles in ensuring that sufficient, clean, and affordable water supplies are available to the citizens of Texas and that those water supplies foster a healthy economy and environment.

Water Planning

The TWDB supports the development of regional water plans and incorporates them into a state water plan for the orderly and responsible development, management, and conservation of the state's water resources. In 1997, the legislature established a new water planning process, based on a "bottom-up," consensus-driven approach. Coordinating this water planning process are sixteen planning groups, one for each regional water planning area (Figure 1). The planning groups, each made up of about twenty members, represent a variety of interests, including agriculture, industry, environment, public, municipalities, business, water districts, river authorities, water utilities, counties, groundwater management areas, and power generation. Each planning group approved bylaws to govern its methods of conducting business and designated a political subdivision, such as a river authority, groundwater conservation district, or council of governments, to administer the planning process and manage any contracts related to developing regional water plans.

The ongoing work of the regional water planning process consists of 10 tasks:

1. describing the regional water planning area;
2. quantifying current and projected population and water demand over a 50-year planning horizon;
3. evaluating and quantifying current water supplies;
4. identifying surpluses and needs;
5. evaluating water management strategies and preparing plans to meet the needs;
6. evaluating impacts of water management strategies on water quality;
7. describing how the plan is consistent with long-term protection of the state's water, agricultural, and natural resources;
8. recommending regulatory, administrative, and legislative changes;
9. describing how sponsors of water management strategies will finance projects; and
10. adopting the plan, including the required level of public participation.

Once the planning group adopts its regional water plan, the plan is sent to the TWDB for approval. The TWDB then compiles information from the approved regional water plans and other sources to develop the state water plan, which is presented to TWDB's governing Board for adoption. The final adopted plan is then submitted to the Governor, Lieutenant Governor, and the Texas Legislature. The latest state water plan, *Water for Texas 2012*, summarizes the dedicated efforts of about 450 planning group members, numerous technical experts, the public, and several state agencies (the TWDB, Texas Parks and Wildlife Department, Texas Department of Agriculture, and Texas Commission on Environmental Quality) between 2007 and 2012. This process has resulted in greater public participation, public education, and public awareness, underscoring the benefits of directly involving local and regional decision makers and the public in water planning.

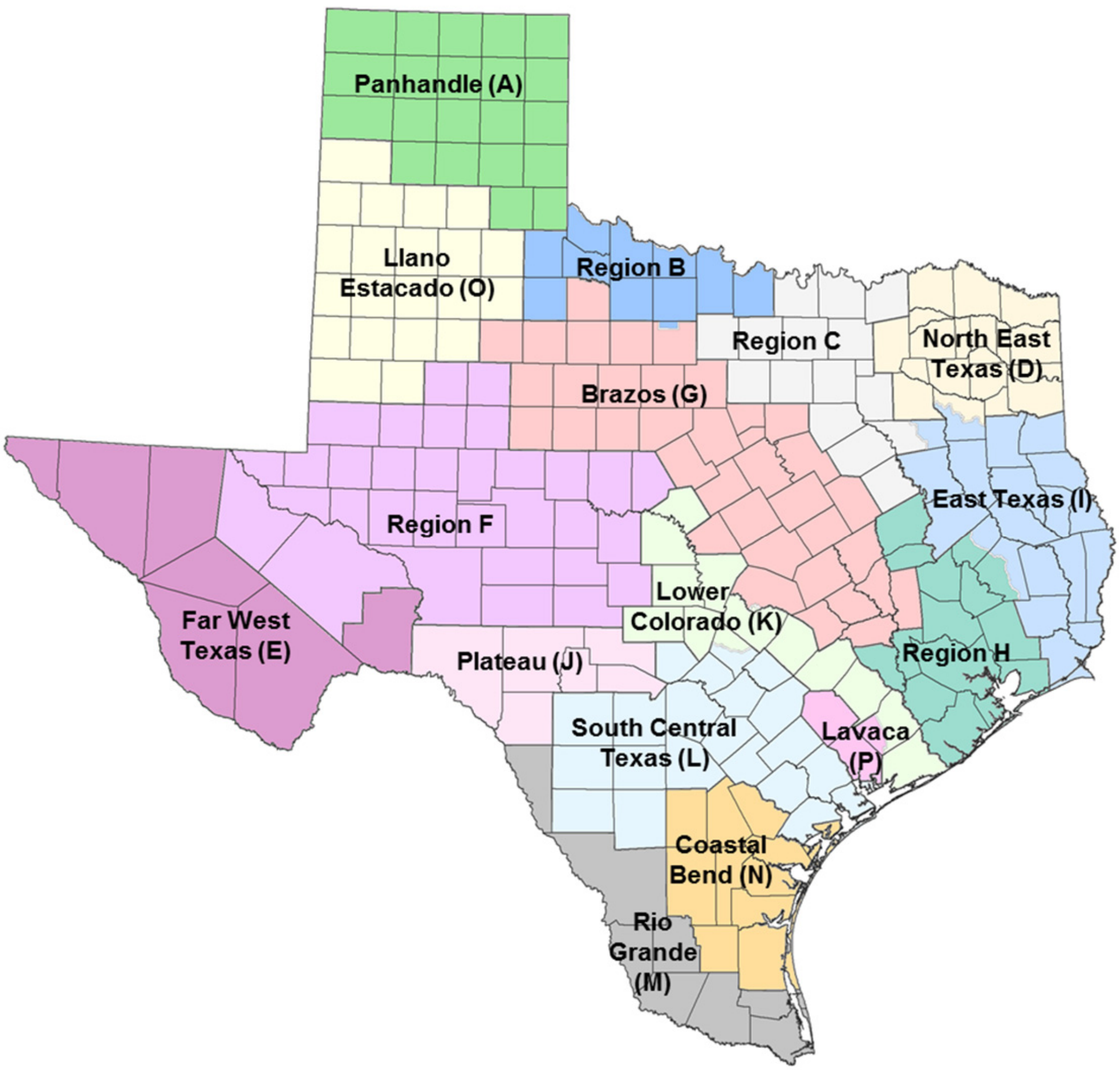

Figure 1. Regional Water Planning Areas of Texas.

Water Project Financing

The Texas Water Development Board administers cost-effective financial programs for constructing water supply, wastewater treatment, flood control, and agricultural water conservation projects. Financial assistance programs can be grouped into three broad categories: federally subsidized programs, state programs, and programs for specific needs. Federally subsidized loan programs include the Clean Water State Revolving Fund and the Drinking Water State Revolving Fund. State programs include the Texas Water Development Fund, the State Participation Program, the Water Infrastructure Fund, and the Rural Water Assistance Fund. The financing for specific needs category includes the Economically Distressed Areas Program and the Agricultural Water Conservation Grant and Loan Program.

The Agricultural Water Conservation Grant and Loan Program

Through the Agricultural Water Conservation Grant and Loan Program, the Texas Water Development Board provides agricultural water conservation loans to political subdivisions either to improve their facilities or to lend to individuals for conservation activities. The TWDB also provides grants to state agencies and political subdivisions for agricultural water conservation initiatives including demonstration projects, technology transfers, and educational programs.

Any political subdivision such as a city, county, soil and water conservation district, underground water conservation district, or irrigation district can apply for an agricultural water conservation loan. Conservation programs or projects are eligible. This includes a conservation program that funds a political subdivision or person for a conservation project.

A conservation program is

- an agricultural water conservation technical assistance program, including a program for an on-farm soil and water conservation plan developed jointly by a landowner, an operator, and a local soil and water conservation district as provided by the Agriculture Code, Chapter 201, Subchapter H;
- a research, demonstration, technology transfer, or educational program relating to agricultural water use and conservation;
- a precipitation enhancement program in an area of the state where the program, in the TWDB's judgment, would be most effective; and
- a water conservation program administered by a state agency or political subdivision to provide loans to persons for conservation projects.

A conservation project

- improves the efficiency of water delivery to and application on existing irrigation systems;
- prepares irrigated land for conversion to dry land conditions;

- prepares dry land for more efficient use of natural precipitation;
- purchases and installs on public or private property devices designed to indicate the amount of water withdrawn for irrigation purposes; or
- prepares and maintains land to be used for brush control activities in areas of the state where those activities, in the TWDB's judgment, would be most effective, including activities conducted under Chapter 203 of the Agriculture Code.

The grant portion of the program provides funding to state agencies and political subdivisions for agricultural water conservation projects. Applications are normally accepted once each year. Grants may be awarded for demonstrations, education, research, technical assistance, and technology transfer. Grants may also be made to political subdivisions to purchase and install, on either public or private property, metering devices to measure agricultural irrigation water use and to quantify water savings resulting from different agricultural water conservation strategies. In reviewing applications for agricultural water conservation grants, the TWDB considers the following:

- the commitment of the entity to water conservation;
- the benefits that will be gained by awarding the grant;
- the degree to which the political subdivision has pursued other available resources to finance the use for which the application is being made;
- the willingness and ability of the political subdivision to raise revenue;
- a finding that the grant will supplement rather than replace finances of the applicant;
- a finding that the grant will serve the public interest. In making this finding, the TWDB will include a finding that the grant will assist in implementing a water conservation management strategy identified in the most recently approved regional water plan or state water plan; and
- the contribution to advancing water conservation in the state.

Of particular importance for recipients of an agricultural water conservation grant are the requirements to document and report actual water savings as a result of the project and to implement a water conservation management strategy from the regional water plan. Each regional water plan presents information regarding the recommended conservation and other types of water management strategies that would be necessary to meet the state's needs in drought conditions, the cost of such strategies, and estimates of the state's financial assistance that would be required to implement these strategies. The conservation strategies can vary greatly depending on the region (Figure 2). In areas of Texas where irrigated agriculture relies primarily on groundwater (such as the High Plains, or Regions A and O), conservation strategies include improvements to on-farm water delivery systems such as low pressure center pivot irrigation systems or installation of drip irrigation systems where applicable. Regions that rely on surface water allocations for agricultural irrigation (such as the Lower Rio Grande Valley, or Region M) might recommend increasing water conservation through land leveling or improvements to water distribution and conveyance systems. According to *Water for Texas 2012*, almost seventeen percent of future water supply volumes resulting from recommended strategies should come from agricultural irrigation conservation.

Figure 2. General location of major irrigated agricultural regions and major rivers in Texas. Map reproduced by TWDB from figure originally published by Texas Society of Professional Engineers (1954).

Agricultural Water Conservation Demonstration Initiatives

In order to increase water conservation efforts in the agricultural sector, the Texas Water Development Board initiated a program in 2004 called the Agricultural Water Conservation Demonstration Initiatives. The purpose of this program is to evaluate and demonstrate the integration of enhanced irrigation water management techniques and diversified farming systems to advance water conservation while maintaining or increasing farm profitability. Demonstrating the appropriate use of this scarce resource and adopting water conservation practices within important economic regions is of paramount importance in maintaining the viability of our agricultural communities. The following is a brief narrative of the two active projects.

Texas Alliance for Water Conservation

In 2004, an eight-year grant of up to $6.2 million was awarded to Texas Tech University for “An Integrated Approach to Water Conservation in the Texas Southern High Plains.” This project is designed to identify, demonstrate, and quantify water-saving agricultural production practices and technologies that will reduce the depletion of groundwater from the Ogallala Aquifer. Twenty-six established demonstration sites exhibit techniques ranging from monoculture cropping systems to fully integrated crop/livestock/forage systems with a broad range of dry land and irrigation technologies, including subsurface drip irrigation and low-pressure center pivot irrigation systems.

The Texas Project for Ag Water Efficiency

A 10-year grant of up to $3.8 million was awarded in 2004 to the Harlingen Irrigation District in the Lower Rio Grande Valley for implementing “Maximization of On-Farm Surface Water Use Efficiency by Integration of On-Farm Application and District Delivery Systems.” The objective of the project is to integrate state-of-the-art irrigation water distribution network control and management techniques with on-farm irrigation management. During the initial phase of the project, a flow meter calibration facility, the Rio Grande Center for Ag Water Efficiency, was constructed in Cameron County. The facility is used for calibrating metering equipment and for training irrigation district personnel from across the state. The facility is also used extensively by Texas A&M AgriLife Extension experts for conducting educational workshops benefiting area producers. An internet based water delivery and tracking system, which can monitor real-time water flow, weather, and water use, was installed at the center. The facility also houses the Harlingen Irrigation District’s pumping plant. District staff can monitor real-time information at the center from their main office in Harlingen and also from the web using mobile applications. This project also oversees demonstration projects aimed at disseminating knowledge of on-farm irrigation water conservation technologies and adaptive management strategies.

TWDB Agricultural Water Conservation Programs

Agriculture in Texas has a long history of providing food and fiber to the people of Texas, the nation, and the world. Population growth is expected to continue resulting in an increased demand for agricultural products even as competition for scarce water resources increases. The economic viability of many regions of the state depends upon a strong agricultural economy. To remain competitive in these markets and to ensure the future of irrigated agriculture in the state, all Texans must continue to conserve our limited water resources. As the largest water use sector in the states, conservation by agricultural irrigators is increasingly the focus of nationwide attention. Working in conjunction with the United States Department of Agriculture Natural Resources Conservation Service, the Texas State Soil and Water Conservation Board, local soil and water conservation districts, and local groundwater conservation districts, TWDB Agricultural Conservation staff assists agricultural producers in maximizing irrigation efficiency.

Agricultural Water Conservation staff distributes funding and manages contracts related to water conservation grants and demonstration initiatives. These projects document actual water savings throughout the state by implementing water conservation strategies identified in regional water plans. Between 2004 and 2013, TWDB agricultural water conservation grants funded over fifty projects covering such topics as efficiency improvements to irrigation conveyance systems, installation and automation of canal check gate structures, irrigation metering equipment, technology transfer, educational outreach and training on irrigation scheduling, irrigation system audits, and demonstrations of irrigation efficiency improvements and soil moisture monitoring.

Agricultural conservation staff also provides agricultural water conservation outreach and educational activities. Through invited speaking presentations, technical assistance, and exhibitions at farm and ranch shows across the state, staff conveys the importance of agricultural water conservation while showcasing those Texas producers already implementing regional water planning strategies to address future water needs. TWDB conservation staff also creates and distributes educational literature to inform producers and the public about not only the importance of water conservation but also best management practices and realistic strategies to accomplish actual water savings.

TWDB agricultural water conservation staff also assists with collection and distribution of water-related data while assisting with regional water planning through development of annual irrigation water use estimates. In Texas, surface water use is permitted by the state and water use is reported by each water right holder. Groundwater withdrawals in Texas are not required to be reported on a statewide level and are managed at a local level by groundwater conservation districts. Because not all agricultural irrigation water use is measured directly, in order to accurately account for water use across all sectors in Texas, agricultural irrigation water use must be estimated.

Staff has developed irrigation water use estimates for Texas by county annually since 1985. These estimates are a key component in the creation of irrigation demand projections as part of the regional water planning process. An estimated 6 million acres of cropland in Texas are irrigated with almost 9 million acre-feet of applied water annually. Because irrigation water supplements effective rainfall, a “wet” year such as 2010 had relatively low statewide irrigation water use versus a “dry” year like 2011. The process of estimating irrigation water use is complex and has evolved over time to include the best data and methods available. Fluctuations in irrigation water use related to local climate, weather patterns, and individual planting decisions complicate the estimation process.

Conclusion

According to *Water for Texas 2012*, irrigated agriculture is the largest water use sector in Texas. Population growth in urban areas of the state is leading to an increase in municipal demands, which are projected to surpass the agricultural sector in the next 50 years. New water supplies are needed to meet this growth and agricultural irrigation conservation is projected to create 17% of the new water supplies in Texas by 2060.

In a time when the forecast for Texas calls for continuing drought conditions, the importance of water conservation has never been more evident. Agricultural producers must maximize irrigation efficiency to maintain productivity and economic viability while the amount of water available for irrigation in Texas declines. The Texas Water Development Board's mission is to provide leadership, planning, financial assistance, information, and education for the conservation and responsible development of water for Texas. Awareness of our most vital resource and the importance of conservation continues to grow throughout the state. By providing financial assistance, educational outreach, and technical guidance to producers, the TWDB agricultural water conservation staff works to ensure the viability of water resources in Texas now and into the future.

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Evaluation of Potential Water Conservation Using Site-Specific Irrigation

K. C. Stone[1], P. J. Bauer, and J. A. Millen

Abstract: *With the advent of site-specific variable-rate irrigation (VRI) systems, irrigation can be spatially managed within sub-field-sized zones. Spatial irrigation management can optimize spatial water use efficiency and may conserve water. Spatial VRI systems are currently being managed by consultants who use either the farmer's familiarity with the field or some other measure of field variability, such as soil maps or soil electrical conductivity. The goal of the research is to provide farmers and consultants a tool to evaluate the potential benefits of implementing VRI. The specific objective of this research is to evaluate the potential water savings using VRI management compared to uniform irrigation management. The 20-year simulation study was carried out on selected fields with varying degrees of soil and topographic variability. The simulated field had 12 soil mapping units with a 65% difference in soil water holding capacity. The 20-year simulation covering all weather conditions for each soil produced only 2 significantly different irrigation management zones. However, when the 20-year period was divided into periods with different ratios of evapotranspiration to rainfall, the simulations identified 5 to 6 management zoned with significantly different irrigation requirements. These results indicate that variable rate irrigation system systems design and management should not be based on long term average weather conditions. Using years with differing weather conditions should be used for potentially identifying management zones for VRI systems. Compared to uniform irrigation management, managing irrigation using multiple management zones saved between 21 and 42 mm of irrigation for specific zones.*

Keywords: Precision farming, Variable-rate irrigation, management zones, water conservation

Introduction

Variable rate irrigation (VRI) systems have the potential to conserve water by spatially allocating limited water resources. Spatial water applications attempt to overcome site-specific problems that include spatial variability in topography, soil type, soil water availability, and landscape features. The VRI systems can also provide differential water application to crops based on spatial crop requirements. Additionally, VRI systems would be an asset in fields that have

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highly variable soil with different water holding capacities. Furthermore, recent droughts throughout the US have highlighted the delicate balance that faces agricultural production in competition with urban, industry, and environmental water uses (Stone et al., 2010). Under these drought conditions, VRI systems can be utilized for water conservation. Sadler et al. (2005) outlined opportunities for conservation including situations where non-cropped areas exist in a field for which irrigation can be turned completely off; situations where a reduced irrigation amount provides specific benefits; and finally, situations where optimizing irrigation amount to adapt to spatial productivity provides quantitative benefits. In this research, we investigated the potential water conservation using VRI for crop production. Our specific objective is to evaluate the potential water savings using VRI management compared to uniform irrigation management using a simple water balance approach.

Methods

A field with highly variable soils and a history of spatial crop production was selected to simulate water requirements for a corn crop. Soil at this site had been mapped on a 1:1200 scale by USDA-NRCS staff in 1984 (USDA-SCS, 1986). Brief descriptions of the 12 soil map units are shown in table 1.

Table 1. Description of soils located under the variable-rate irrigation system at Florence, SC (after Sadler et al., 2002)

Symbol	Soil Classification
BnA	Bonneau loamy fine sand (lfs), 0% to 2% slopes
Cx	Coxville loam
Dn	Dunbar lfs
Do	Dunbar lfs, overwash
ErA	Emporia fine sandy loam (fsl), 1% to 2% slopes
GoA	Goldsboro lfs, 0% to 2% slopes
NbA	Noboco lfs, moderately thick surface, 0% to 2% slopes
NcA	Noboco lfs, thick surface, 0% to 2% slopes
NfA	Noboco fsl, 1% to 2% slope
NkA	Norfolk lfs, moderately thick surface, 0% to 2% slopes
NoA	Norfolk lfs, thick surface, 0% to 2% slopes
NrA	Norfolk fsl, 1% to 2% slopes

The water holding capacity for these soils were estimated using the soil properties in the DSSAT soils database (Jones et al., 2003) and from previous modeling research by Sadler et al. (2000). The soil had a wide range of water holding capacities (Figure 1). The water holding capacities of the top 12 inches of the soils ranged from approximately 42 mm to 70 mm.

These soils were then used to simulate a 20-year water balance under the VRI system. The water balance was accomplished in a Microsoft Excel spreadsheet. The equation for the simple daily water balance was:

$$S_{i+1} = S_i + Rain_i - ET_{ci} - Runoff_i - Drainage_i$$

Where S_i was the soil storage on day I, and ET_{ci} = crop evapotranspiration. When the soil storage exceeded saturation, the excess was defined as runoff. Drainage was calculated as the difference between the maximum soil water holding capacity and saturation. Crop evapotranspiration was calculated based on the ASCE standardized reference evapotranspiration equation (Walter et al., 2000) method and crop coefficients for a corn crop. The weather parameters were collected from on on-site weather station.

The simulated water balance was calculated for a corn crop grown under the VRI system. The four simulation scenarios were simulated: 1) a uniform irrigation using the soil with the largest area under the VRI system (NkA); 2) using the individual soils as management zones (ie. 12 management zones); 3) 2 management zone (zone 1: Bonneau, NcA, NrA,NoA, NkA, NfA, NnA; zone2: NbA, Emporia, Dunbar, Coxville, Goldsboro); and 4 management zones (zone 1: zone 1: Bonneau, NcA, NrA; zone 2: NoA, NkA, NfA; zone3: NnA, NbA; zone 4: Emporia, Dunbar, Coxville, Goldsboro).

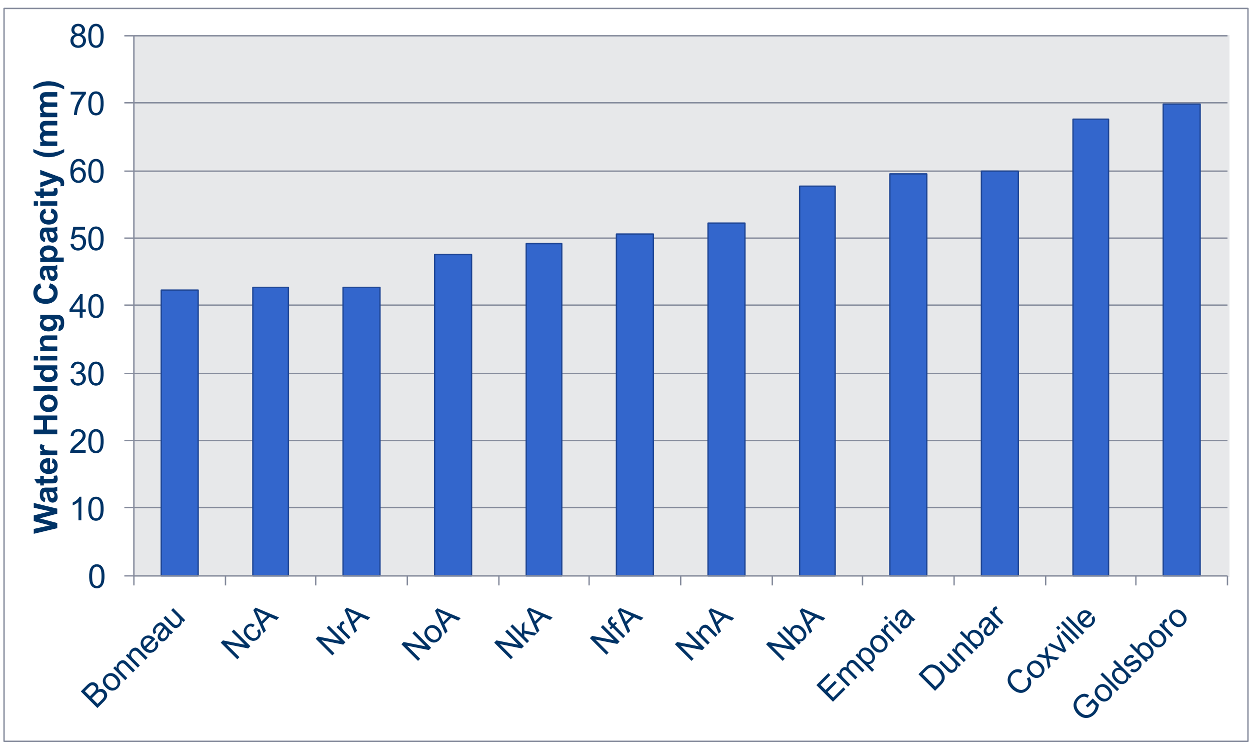

Figure 1. Soil water holding capacities for the 12 soil map units under the variable-rate irrigation system at Florence, SC.

The growing season rainfall was highly variable during the 20-year simulation period (figure 2) and encompassed both wet and drought years. The account for differing weather patterns, we calculated the ratio of growing season cumulative potential ET to rainfall. We then in addition to a simulation covering all years, we simulated the water balance for years with the ET-Rainfall ratios of <50%, 50 To 60%, 60 to 75%, and >75%. We referred to these ratios as drought years.

Results

The simulations of water balance over the 20-year simulation using the individual soils as management zone are shown in table 2. The simulation results for the entire 20-year period had average irrigation requirements ranging from 230 to 271 mm. The 20-year simulation produced only two significant groups of soil (or potential management zone). However, using long-term simulation may mask years where drought conditions existed. When the simulations were divided into drought years, the results were quite different (table 2). The drought years with ET/Rainfall ratio less than 50% required the greatest irrigation as expected with irrigation ranging from 303 to 318 mm. Similar distributions of irrigation requirement were seen in the other ET/Rainfall ratio categories. Overall these categories, there were from 5 to 6 significantly different management zones identified. This was in contrast to the simulation covering all conditions which only had 2 significant management zones.

Table 2. Simulated average irrigation requirements for the for 12 soil maps units for years with different levels of drought conditions and for a simulation over all years.

Soil	Drought (% of ET_{ref} / Rainfall)				All Years
	<50%	50 to 60%	60 to 75%	> 75%	
	Irrigation (mm)				
Bonneau	318 A*	290 A	277 A	213 A	271 A
Coxville	294 E	258 F	243 EF	177 E	240 B
Dunbar	301 D	268 E	249 DE	189 D	249 AB
Emporia	303 D	268 E	249 DE	189 D	249 AB
Goldsboro	294 E	258 F	241 F	177 E	239 B
NbA	303 D	271 DE	251 D	196 C	252 AB
NcA	318 A	290 A	277 A	213 A	271 A
NfA	313 BC	279 BC	260 BC	205 B	261 AB
NkA	313 BC	283 B	260 BC	207 AB	263 AB
NnA	311 C	275 CD	254 CD	205 B	259 AB
NoA	316 AB	283 B	264 B	208 AB	265 A
NrA	318 A	290 A	277 A	213 A	271 A
# of Zones	**5**	**6**	**6**	**5**	**2**

* Irrigation depths for a given drought condition with different letters were significantly different at the 95% level.

We then calculated the irrigation requirements with the water balance for a specific number of predefined management zones (table 3). The management zones used groups of soils with similar water holding capacities. The scenario with one management zone required the greatest overall irrigation. Under this scenario, some areas of the field may have been over or under irrigated. The scenarios with two and four management zones had differing irrigation requirements depending upon the average water holding capacity of that specific zone. Using a management zone approach as simulated could save or conserve from 21 to 42 mm of irrigation in specific management zone compared to a uniform irrigation.

Table 3. Simulated irrigation requirements for the one (uniform), two, and four management zones irrigation scenerios.

Mgt. Zone	Drought (% of ET_{ref})											
	<50%			50 to 60%			60 to 75%			>75%		
	# of Mgt. Zones			# of Mgt. Zones			# of Mgt. Zones			# of Mgt. Zones		
	One	Two	Four	One	Two	Four	One	Two	Four	One	Two	Four
	Irrigation (mm)											
1	313	316	320	283	285	293	260	269	283	206	211	215
2	.	295	313	.	259	279	.	242	259	.	181	206
3	.	.	300	.	.	268	.	.	248	.	.	194
4	.	.	293	.	.	256	.	.	241	.	.	174
Difference		21	27		26	37		27	42		30	41

Summary and Conclusions

The water balance of a corn crop was simulated using a 20-year weather record at Florence, SC. The simulated field had 12 soil mapping units with a large difference in soil water holding capacities. The 20-year simulation covering all weather conditions for each soil produced only 2 significantly different irrigation management zones. However, when the 20-year period was divided into periods with different ratios of evapotranspiration to rainfall, the simulations identified 5 to 6 management zoned with significantly different irrigation requirements. These results indicate that variable rate irrigation systems design and management should not be based on long term average weather conditions. Irrigation design should be utilize periods where irrigation demands are greater. Additionally, using this simulation approach may be useful in determining management zones for VRI systems.

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The Criticality of the Agricultural Distributor for Poverty Reduction in Least Developed Countries

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Abstract. *Agricultural production in the poorest countries of the world has remained stagnant over the past ten years while poverty and undernourishment have increased. In order to maintain minimum caloric intake for the projected tripling of population in sub-Saharan Africa, production must increase by 100% by 2050. Agricultural methodologies must employ sustainable agricultural practices in order to achieve two major objectives: because agriculture is the major cause of global greenhouse gas emissions, and, climate variability is the primary determinant of agricultural productivity agricultural regimes must be adaptive and provide means of mitigating environmental damage; and, as evidence has shown, and will be explicated below, sustainable agricultural practices utilize few inputs and provide greater yields and profitability for the grower. This paper cites evidence that the current paradigm of providing Development Assistance does not significantly increase growers' producer supply curves and does not reduce poverty or undernourishment in Least Developed Countries. This paper posits that analyses centered on Market Failure to explain lack of production and the eventual prescription of government interventions overlooks an important paradigm for improved agricultural production that has been successful in other, developed, communities. This paper posits that to improve production within the context of global environmental change an effective model must integrate agro-economic institutions and provide epistemic space for sustainable agriculture irrigation regimens. This paper posits that the critical agro-economic institution for smallholders in Least Developed Countries is the irrigation distributor network and provides four models of irrigation distribution in Africa*.

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Keywords. Agriculture in the Anthropocene, Sustainable Agricultural Production irrigation distributors, irrigation distributors, poverty reduction, agro-economic institutions

Introduction

This paper asks that, given the positive and significant correlation between sustainable agricultural practices and socio-ecological improvement, why is it that agricultural production in the Least Developed Countries (LDCs) has not significantly increased over the past decade? Or, to quote an oft-asked question: "If economists are so smart, why is Africa so poor?" (Haber, North, & Weingast, 2003). The question is of serious concern but becomes a much more urgent problem when taking into account the massive increase in population that is projected to occur over the next thirty years which will demand a 70 percent increase in global production. Of further concern is evidence that water and land management have the greatest and most significant anthropogenic impacts on greenhouse gas emissions (Wollenberg, Nihart, Tapio-Bistrom, & Grieg-Gran, 2012; Hayashi, Akimoto, Tomoda, & Kii, 2012; Ospina & Heeks, 2012; Adams, Hurd, Lenhart, & Leary, 1998; Maeda, Pellikka, Siljander, & Clark, 2010; Folke, et al., 2004; Bellarby, Foereid, Hastings, & Smith, 2008). "The earth's largest terrestrial store of carbon is soil (and), since the Industrial Revolution, soil carbon emissions from land-use change and agricultural activities have accounted for about 19% of total atmospheric carbon emissions" (Tennigkeit, Kahrl, Wölcke, & Newcombe, 2012, p. 302) while indirect total emissions caused by agricultural production account for about one-third of all greenhouse gas emissions (Wollenberg, Tapio-Biström, & Grieg-Gran, 2012).

Conway has called for a new "Doubly Green Revolution" (Conway, 1999, p. 17) to significantly increase crop production in LDCs while '"conserving natural resources and the environment" (Conway, 1999, p. 29). The process of sustainable agricultural production (SAP), also called climate-smart agriculture (Grainger-Jones, 2011), or smallholder systems innovations (Bossio, Jewitt, & van der Zaag, 2011) has been shown to act as a positive and significant independent variable that explains decreases in poverty and malnutrition and mitigation of global environmental change. SAP represents a win-win for smallholder farmers and the Earth's system in that it provides smallholders greater profitability while reducing the impacts of global enironmental chan (Pretty, Noble, Bossio, Dixon, Hine, & Penning de Vries, 2006, p. 1114).

This paper posits that the investigation into the paucity of increased agricultural production starts with an understanding of private, agro-economic institutions that have not been allowed to function to their maximum efficiency because of epistemically-poor government and NGO interventions. In other words, government programs and NGO funding and programs ignore the critical relationship between the irrigation manufacturer, distributor, and grower. The critical gap in current paradigms is institutional.

The structure of the paper is divided into eight brief sections: The next, or, second section will provide a background summary of the socio-economic status and projections of the LDC populations who make up the central level of analysis of this study. The third section explicates the state of agricultural production in LDCs which remains stagnant over the past decade. The fourth section describes the state of water security in LDCs, the nature of the Anthropocene, and the impacts of global environmental change on the most vulnerable countries. The fifth section describes in detail the processes of SAP and a detailed literature review of case studies where SAP has been implemented. The sixth section provides an overview and critical analysis of current Development models that are designed to increase agricultural production and reduce poverty. The seventh section describes the distributor model that is posited as the critical element for agricultural production increases within the context of global environmental change. The final section is a conclusion of the paper followed by references.

Background

Socio-Economic Status and Projections in LDCs

Between 2011 and 2100, the population of high-fertility countries, which include the majority of Least Developed Countries (LDCs) in sub-Saharan Africa, is projected to triple, passing from 1.2 billion to 4.2 billion (UNFPA). LDCs constitute the poorst 48 countries of the world. In LDCs, the number of extremely poor people (living on less than $1/day) increased by over 3 million from 2002-2007 to 1.3 billion, the distribution of people in the adult population earning less than $1.25/day doubled from 18 percent to 36 percent, and 2.6 billion people live on less than $2/day (UN, 2012) . The total number of people in LDCs who are undernourished (living on less than 3000 kcal/day/capita) increased by over 5 million from 2002-2007 (UNCTD, 2010) . Fully 95 percent of all undernourished people live in the developing countries (UN, 2012).

One particularly insidious and revealing indicator of undernourishment in LDCs is the incidence and severity of childhood stunting. Stunting is defined as "the height (or length)-for-age more than 2 Standard Deviations (SD) below the median of the National Center on Health Statistics and World Health Organization (NCHS/WHO) international reference" (WHO). "Even though the prevalence of stunting in all developing countries declined from 47% in 1980 to 33% in 2000...progress was uneven across regions...Stunting had increased in Eastern Africa...had modest improvements in Northern Africa and had presented very little progress in Western Africa" (de Onis, Frongillo, & Blossner, 2000, p. 1). Table 1, below, illustrates that stunting has not been significantly reduced, particularly in Eastern and Western Africa, since 1980 (de Onis, Frongillo, & Blossner, 2000).

Table 1. The Prevalence of childhood stunting in Africa 1980-2005 (pct)

Region	1980	1985	1990	1995	2000	2005
Africa	40.5	39.2	37.8	36.5	35.2	33.8
Eastern Africa	46.5	46.9	47.3	47.7	48.1	48.5
Northern Africa	32.7	29.6	26.5	23.3	20.2	17.0
Western Africa	36.2	35.8	35.5	35.2	34.9	34.6

Agricultural Production in LDCs

The Food and Agricultual Organization (FAO) of the UN has determined that agricultural production needs to increase by 70 percent overall (Pretty, Noble, Bossio, Dixon, Hine, & Penning de Vries), and by 100 percent in developing countries by 2050, to cope with an overall increase from 6.5 to 9.0 billion people (Bruinsma, 2009). Evidence is abundant that agricultural growth is key to poverty reduction in countries that depend largely on agriculture for their livelohoods (ADB, FAO, IFAD, IWMI, World Bank, 2006). Moreover, a great deal of evidence-based studies show that there is a direct and positive correlation between the growth of irrigation and reduction of poverty. Hussain and Wijerathna shows that "on average, a 1-percent increase in agricultural productivity level will reduce incidence of poverty by 0.31 percent" (Hussain & Wijerathna, 2004). Case studies establishing the linkage between efficient irrigation systems and poverty reduction are many— in Kenya (Ngigi, Thome, Waweru, & Blank, 2010); Pakistan (Hussain, Z, & Ashfaq, 2006); Ethiopia (Gebregziabher & Namara, 2009); and, Burkina Faso (Dembele, Yacouba, Keita, & Sally, 2011), for example— and report direct and indirect benefits of irrigation, including increased farmer consumption and assets. Additionally, farmers that have irrigation systems tend to informally share more with their communities than non-irrigators (Dillon, 2011). However, over the past decade, growth in agricultural production in LDCs has been virtually stagnant (UNDP, 2011; Bruinsma, 2009; World Bank, 2012). In addition, projections imply that agricultural production will decline in many parts of the developing world. Reports indicate that per capita food production is already declining in parts of sub-Saharan Africa (Grainger-Jones, 2011) and new data suggests that rainfed crop yields in some African countries are projected to decline by 50 per cent by 2010 due to climate change (IFAD, 2012). World Bank data illustrate the stagnation of agricultural growth in LDCs (World Bank, 2012).

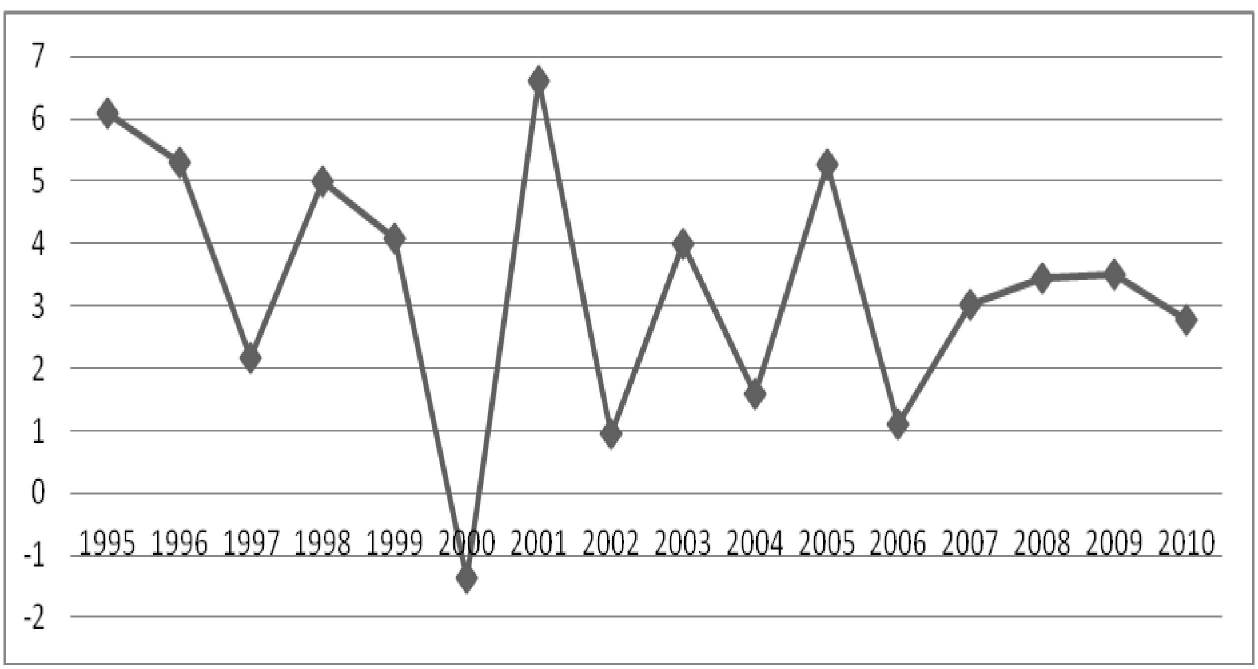

Figure 1 LDC annual growth from agriculture 1995-2010 (percentage) (World Bank, 2012)

Grain production in sub-Saharan Africa is often cited as an indicator of agricultural production. From 1960-2010 the average grain production has averaged at or below 1 ton/hectare (Makurira, Savenije, Uhlenbrook, Rockstrom, & Senzanje, 2011, p. 1697) and is illustrated below in the graph. There has been an approximate 5 percent growth in grain production from 2000-2010 but only a 3 percent growth from 1970-2010. In order to cope with the overall 40 percent increase in world population, grain production has to increase by an additional billion tons of cereals by 2050, as compared with production in 2005/07 (Bruinsma, 2009, p. 2).

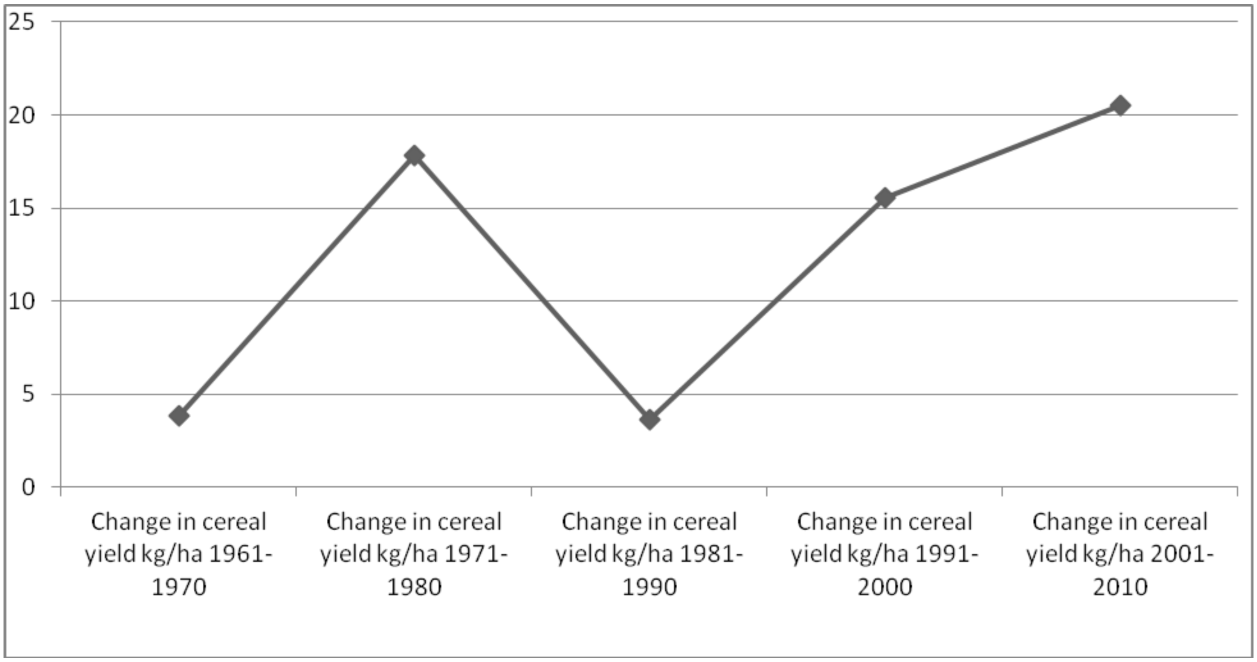

Figure 2 Grain production growth in LDCs from 1960-2010 (percentage) (Makurira, Savenije, Uhlenbrook, Rockstrom, & Senzanje, 2011)

Water Scarcity, the Anthropocene, and Impacts of Environmental Change

In addition to the socio-economic challenges faced in LDCs over the next generation, it is also important to note that those most in need of poverty and undernourishment reduction live in the most water-scarce and environmentally vulnerable environments. Currently, about 700 million people in 43 countries suffer from water scarcity. A region experiences water stress when annual water supplies drop below 1,700 m^3/capita. When annual supplies drop below 1000 $m^{3/}$capita the population faces water scarcity, and when annual supplies drop below 500 m^3/capita, the population faces absolute water scarcity (UN, 2005) . "By 2025, 1.8 billion people will be living in countries or regions with absolute wter scarcity, and two-thirds of the world's population could be living under water-stressed conditions (FAO, 2007).

Water scarcity is likely to increase over the next 30 years in vulnerable communities because agriculture is the major cause of global greenhouse gas emissions and "climate variability is the primary determinant of agricultural productivity" (Adams R. , Hurd, Lenhart, & Leary, 1998, p. 19). The majority of agricultural emissions, approximately 74 percent, originate in low and middle-income countries, where smallholder farmers predominate (Wollenberg, Tapio-Bistrom, & Grieg-Gran, 2012, p. 4). A central reason for the increase in greenhouse gas emissions in LDCs, is the propensity for farmers to increase crop production by expanding cultivated areas rather than increasing yields on current agricultural lands. Typically, the expansion of land involves cutting forested areas. In sub-Saharan Africa about 95 percent of the total agricultural land is rainfed agriculture so increasing yields on established agricultural land is challenging (Bossio, Jewitt, & van der Zaag, 2011, p. 1683).

The Anthropocene

The Anthropocene is the new epoch in Earth history (Steffen, Grinevald, Crutzen, & McNeill, 2011) that is distinguished by the sizeable and siginficant impact of the human imprint on the global environment. The anthropogenic impacts of humankind on the global enviornment have been quantified by Rockstrom, et al, and codified into Planetary Boundary Theory. Climate change is only one of a number of planetary boundaries that make up the Earth-system processes and associated thresholds that, of crossed, could generate unacceptable enviornmental changes (Rockstrom, et al., 2009). Of particular salience for this paper is that land and water management is key to mitigating the seven, currently quantifiable, planetary boundaries. "Water and land management are the primary media through which climate change will impact people, ecosystems and economics" (Sadoff & Muller, 2009).

Sustainable Agricultural Production; the Process and Literature Review

Sustainable agricultural production methods are instruments and regimes that growers draw from a tool kit in order to increase production . A key study elegantly illustrates the "synergies and tradeoffs between productivity, climate change adaptation, and greenhouse gas mitigation" (Bryan, Ringler, Okoba, Koo, Herrero, & Silvestri, 2011, p. 3). Bryan, et al, list the activities of sustainable agriculture (productivity impacts) and corresponding climate adaptation benefits and greenhouse gas mitigation potential and finds that improved crop varieties; changing plant dates; improved crop rotation with legumes; appropriate use of fertilizer and manure; incorporation of crop residues; reduced tillage; agroforestry; irrigation and water harvesting; bunds; terraces; mulching; grass strips; ridge and furrow, and; diversion ditches, all increase yields (with the excepted impact of reduced likelihood of crop failure for the 'changing plant date' activity) and all have positive mitigation potential. Reganold, et al, point out that "sustainable agriculture does not represent a return to pre-industrial revolution methods; rather it combines traditional conservation-minded farming techniques with modern technologies. Sustainable systems use modern equipment, certified seed, soil and water conservation practices and (the)...emphasis is placed on rotating crops...and controlling pests, naturally" (Reganold, Papendick, & Parr, 1990, p. 115). Makurira, et al, compared a combination of three methods of sustainable agriculture which he terms "farming system innovations" ((Makurira, Savenije, Uhlenbrook, Rockstrom, & Senzanje, 2011, p. 1696). His Tanzania project looked at the effects of runoff diversion (RD), on-site water harvesting (WH), conservation tillage (CT) at four sites using traditional hand-hoe methods and found an increase of maize yields of up to 4.8 tha^{-1} over the current average of less than 1tha^{-1} (Makurira, Savenije, Uhlenbrook, Rockstrom, & Senzanje, 2011, p. 1696). .

"The idea of agricultural sustainability centers on food production that makes the best use of nature's goods and services while not damaging these assets" (Pretty, Noble, Bossio, Dixon, Hine, & Penning de Vries, 2006). Even more succinctly, "Sustainable agriculture is concerned with the ability of agroecosystems to remain productive in the long term" (van der Werf & Petit, 2002, p. 131). The two keys to mitigating any deleterious impacts of irrigated agriculture are: (1) to provide scientifically-derived evidence that the adoption of sustainable agricultural practices leads to profitable increases in production and (2) to make those methods available and accessible to smallholder farmers. Evidence shows that interventions to increase agricultural sustainability reduces pesticide use, increases yields and improves soil (Pretty, Noble, Bossio, Dixon, Hine, & Penning de Vries, 2006). Pretty, et al. showed "the extent to which 286 interventions in 57 poor countries covering 37 million ha (about 3% of the cultivated area in developing countries) have increased productivity on 12.6 million farms while improving the supply of critical environmental services" (Pretty, Noble, Bossio, Dixon, Hine, & Penning de Vries, 2006, p. 1114). Sustainable agricultural practices such as minimum crop tillage and integrated pest and nutrient management regimes helped increase "average yields by 79% (geometric mean 64%). Potential carbon sequestered amounted to an average of 0.35Gt/Cy (gross tons per calendar year). One of the parameters of sustainable agriculture is integrated pest management. Of projects in Pretty's study with pesticide data, 77% resulted in a decline in pesticide use by 71% while yields grew by 42%" (Pretty, Noble, Bossio, Dixon, Hine, & Penning de Vries, Resource-Conserving Agriculture Increases Yields in Developing Countries, 2006, p. 1114).

Lin suggests that building resilience through crop diversification is a rational and cost-effective way for agriculture to adapt to changing climatic conditions (Lin, 2011, p. 183). The specific benefit of crop diversification is to reduce the outbreak and intensity of pathogenic transmission which is a typical phenomenon of monoculture agriculture (Lin, 2011). Salient to this paper is Lin's emphasis on the importance of the ability to communicate adaptation options to farmers and the local community (Lin, 2011, p. 190). Lin stresses the need for partnerships among stakeholders and, in particular, farmers and scientists. While Lin overlooks the role of the irrigation distributor it is implicit in his.

According to Bellarby, et al, "the total global contribution of agriculture, considering all direct and indirect emissions, is between 8.5-16.5 Pg CO_2, which represents between 17 and 32% of all global human-induced GHG emissions, including land use changes" (Bellarby, Foereid, Hastings, & Smith, 2008, p. 5). Bellarby, et al, suggest that agriculture provides a wide range of mitigation options including: cropland management, restoration of organic soils, improved water and rice management, increasing the efficiency of fertilizers, etc (Bellarby, Foereid, Hastings, & Smith, 2008, p. 9).

Similarly, other studies show significant and positive economic benefits from practicing sustainable agricultural practices (Smith, et al., 2008) and McCarthy in (Branca, McCarthy, Lipper, & Jolejole, 2011) (CCAG 1.33).

A key study elegantly illustrates the "synergies and tradeoffs between productivity, climate change adaptation, and greenhouse gas mitigation" (Bryan, Ringler, Okoba, Koo, Herrero, &

Silvestri, 2011, p. 3). Bryan, et al, list the activities of sustainable agriculture (productivity impacts) and corresponding climate adaptation benefits and greenhouse gas mitigation potential and finds that improved crop varieties; changing plant dates; improved crop rotation with legumes; appropriate use of fertilizer and manure; incorporation of crop residues; reduced tillage; agroforestry; irrigation and water harvesting; bunds; terraces; mulching; grass strips; ridge and furrow, and; diversion ditches, all increase yields (with the excepted impact of reduced likelihood of crop failure for the 'changing plant date' activity) and all have positive mitigation potential. The overall climate adaptation benefits were reduced yield variability and improved soil fertility (Bryan, Ringler, Okoba, Koo, Herrero, & Silvestri, 2011, pp. 3-4). Salient to this study is the conclusion that Bryan, et al, reach in their study. Namely, that farmers (in Kenya) "do not fully recognize the interlinkages between agricultural productivity, climate change adaptation, and GHG mitigation. Rather farm decisions depend largely on productivity considerations" (Bryan, Ringler, Okoba, Koo, Herrero, & Silvestri, 2011, p. 35). They continue, "This is a significant gap that the government, NGOs, and extension agents will need to address in Kenya and elsewhere in the developing world for agricultural GHG mitigation to become an effective development strategy" (Bryan, Ringler, Okoba, Koo, Herrero, & Silvestri, 2011, p. 35).

Current Models for Development

In a word, the model for development of agriculture in LDCs has had two broad elements: funding; and, research and development of new technologies. To a lesser degree, the Development community has also tried to provide incentives, or subsidies, to encourage sustainable growth.

Market Failure Interventions

The rationale for funding and interventions of NGOs in African agriculture are based on analyses of market failure in African agriculture. The reasons for market failure often cited in the literature are several. "Inefficient allocation of resources (and), the breakdown of transmission mechanisms when people are socially excluded from markets" (Dorward, Farrington, & Deshingkar, 2004) are often cited. Other reasons for the lack of production within the context of market failure that precipitated government interventions are "inefficiencies created by incomplete institutional and physical infrastructure and imperfect competition" (Barrett & Emelly, 2005). The objectives of the interventions are to "get prices right (and) get institutions right" (Barrett & Emelly, 2005).

A later intervention to correct market failure was to introduce new and better technology. The constraints to widespread adoption of new technology were discussed by the United Nations Ministerial Conference of the Least Developed Countries in 2007. The internal and external difficulties to the adoption of technology to increase agricultural development were cited as, "low productivity; inflexible production and trade structures; low skill capacity; low life expectancy; low educational attainments; poor infrastructure; and, deficient institutional policy frameworks" (United Nations Ministerial Conference of the Least Developed Countries, 2007, p. 1).

Other constraints that are often cited and serve as attract intervention strategies are: the tension between customary and statutory laws (Gebregziabher & Namara, 2009; Maganga, 2003); unpredictable and variant rainfall (Bossio, Jewitt, & van der Zaag, 2011); the imbalance of gender in the agricultural sector (Phillip, Nkonya, & Oni, 2008).

Funding

Funding to correct market failures, from 1995 to 2009, by the mechanism of Net Official Development Assistance (ODA) to LDCs rose from $17 billion to $40 billion (in current US$) (UNDP, 2010). In 2010 net ODA flows from members of the Development Assistance Committee (DAC) of the OECD reached $128.7 billion, which is the highest level of aid in the history of OECD (OECD, 2013). The FAO suggests that in order to feed the developing world in 2005 it will be necessary to annually invest in developing country agriculture $83 billion (FAO).

Funding for R&D

One central model for agricultural development from the middle of the 20th century onward has been to invest in agricultural research and development (R&D). The assumption by Development is that "the world's agricultural economy underwent a remarkable transformation during the 20th century as the result of agricultural productivity growth, which was primarily generated by agricultural R&D financed and conducted by a small group of rich countries—especially the United States, but also Japan, the United Kingdom, France, and Germany" (Pardey, Alston, & Piggott, 2006, p. 3). Approximately $37 billion in total R&D was generated, worldwide, in agriculture in 2000 but has dwindled somewhat since.

Incentives and subsidies

Another type of intervention that the Development community has attempted to encourage the adoption of sustainable agricultural practices (considered a public good) are subsidies. The typical incentive-based intervention program to financially stimulate sustainable production has been to subsidize programs to reduce carbon footprints. Direct incentives for smallholder farmers to adopt mitigation practices are not particularly effective for a number of reasons: uncertainties and high transaction costs of identifying carbon sequestration practices (De Pinto, Ringler, & Magalhaes, 2012, p. 61); lack of standards, particularly in developing countries, to measure GHG emissions (Wollenberg, Tapio-Biström, & Grieg-Gran, 2012, p. 21), and; carbon payments available to smallholders are generally several factors lower than potential profits from higher yields (Tennigkeit, Kahrl, Wölcke, & Newcombe, 2012, p. 152).

Indirect incentives are derived when the same sustainable agricultural practices that mitigate greenhouse gas emissions are implemented that result in higher agricultural yields and profit. While agriculture has the greatest economic potential contribution to greenhouse gas reductions, it is the farmer's perspective that increased soil fertility, for example, is of greater emphasis than are potential payments for mitigation, which are considered as bonuses (Lee & Newman, 2012, p. 98). Smith and Wollenberg point out that the agriculture has the potential to reduce somewhere between 25-78% of all CO_2 gases {as cited in (Smith & Olesen, 2010; Smith, et al., Agriculture, 2007)}. "The annual economic mitigation potential is estimated to be worth between $32 billion and $420 billion. About 70% of the potential arises from developing countries" (Smith & Wollenberg, 2012, p. 50). Mitigation, adaptation and sustainable agricultural practices represent a synergistic model that can serve to incentivize smallholders in LDCs. (Smith & Wollenberg, 2012, pp. 50-51).

However, growers are rational decision-makers. "...a farmer will adopt mitigation practices when the net present value of farming with these practices is greater than that of the alternatives" (De Pinto, Ringler, & Magalhaes, 2012, p. 62).

A key reason why interventions to correct markets are not effective is because "the 2 billion smallholder farmers produce 70% of the world's food crop which never enters the market" (Noble, 2013).

The grapha and table below illustrate the growth in ODA funding and the stagnation of agricultural production. This data is important but the implications for the continuation of this trend in light of impending population growth in the next thirty years are significant and negative.   As is clearly indicated in the figure below, there is an insignificant relationship between total funding and changes in agricultural production. This analysis does not include an examination of the potential counterfactual circumstances. It may be that were there not funding at the levels indicated, production may be much lower than were no funding available. Nonetheless, the level of funding does not encourage increased production to the levels required.

Figure 3 Financial Input, Agricultural Growth, and Population in LDCs

The Distributor Model

The distributor/grower/manufacturer model, diagrammed below, is the successful paradigm for increases in agricultural production in developed countries.

The function of the irrigation distributor is to enable growers to achieve greater efficiencies, higher yields, cost-effective methodologies for their farming operations, regardless of scale, within the context of good environmental stewardship. The distributor interfaces, on an exclusive basis, with manufacturers of irrigation, agricultural tool and implement, nutrient, and chemical manufacturers. The distributor serves as the wholesale procurer and distributor of equipment. It is the responsibility and commitment of the distributor to represent the products he/she sells honestly, at a fair market price, and provide support services for those products and their applications.

It is has been established above that sustainable agricultural production leads to optimal yields, greater efficiencies, higher profits, and mitigates environmental damage. It is incumbent upon the manufacturers, NGOs, academic institutions, economists, environmentalists, climatologists, social scientists, to ensure that the agricultural and irrigation distributor is educated in this process. The distributor is not only the agent of the manufacturer and the grower. The distributor is the indispensable dissemination source for agricultural information for two reasons: 1) the task of informing individual smallholders about methodologies or technology by an academic institution or NGO is virtually impossible. In order for the distributor to become successful he/she must reach out to the smallholder community to develop a consistent customer base. One distributor will have direct access to hundreds or thousands of smallholder farmers; 2) the smallholder, like any farmer in the world, looks first to the distributor for support and information, on a regular basis. Irrigation is a dynamic process. As the great Nigerian writer, Chinua Achebe, wrote, "Things Fall Apart" (Achebe). All irrigation system components: pumps; valves; emitters; conveyance pipes; fittings, etc, need regular repair and maintenance. The critical actor for any farmer is the agent who stocks spare parts.

The critical distinction between the distributor model and the development model, is the interlinked and interdependent financial relationship that exists between the three key actors: grower; distributor; and, manufacturer. As illustrated below, these three actors are tied together.

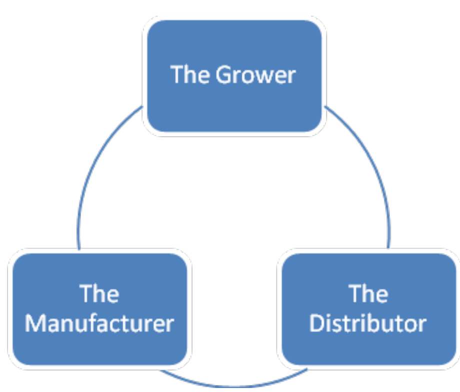

Figure 4 The Distributor Model

The financial success of all three are dependent on each other. The manufacturer's lifeline depends upon purchases of his/her equipment by the distributor; the distributor's lifeblood depends upon the successful performance of the manufacturer's product and the purchases of the grower; the grower is dependent upon the reliability of the manufacturer's products and the support and service, including availability of spare parts, of the distributor. Training is provided by the manufacturer to the grower through the good offices of the distributor. The key to the sustainable success of this model is the relationships that are built by all three actors and the formal commitment of the manufacturer to only sell products to the distribution network, never directly to the grower.

The Distributor Models

There are four typical distributor models: the private entrepreneur; collective; partnership; and, NGO Farm Center.

Entrepreneur

The entrepreneur model is the most common in developed countries. This model stipulates that a private agent owns and operates a dealership, employs a full staff and stocks equipment. In essence, the entrepreneur runs a full service store for his/her clients which, for the most part, are privately held farming operations. A typical irrigation dealer in the United States will stock upward of 14,000 parts to serve all the irrigation components in the field (Davis, 2013). For example, in California, irrigation dealers in the agricultural sector provide design and engineering services, installation of irrigation systems, service work for components and systems, and maintenance. They sell individual components and spare parts and provide full system sales and rentals. The designers are "certified irrigation designers", and "Certified Agricultural Irrigation Specialists" (Agri-Valley, Inc.). Installations "include mechanical sprinklers, drip irrigation systems, sub surface systems, PVC transport systems, solid set sprinklers and all aspects of aluminum pipe" (Agri-Valley, Inc.).

Agricultural dealers typically sell irrigation, chemical, pest control, fertilizer, injection equipment, mulch and row covers, spray gear, hardware and safety equipment (Water Tech Ag Supply). Within the irrigation category typical sub-categories are: drip tape; filters; PVC pipe; layflat hose and fittings; Schedule 40 PVC fittings; Schedule 80 PVC fittings; fabricated fittings; pumps, parts and accessories, hose and tubing and fittings, drain pipe, accessories and fittings, irrigation valves; emitters and sprinklers, aluminum pipe; pivots, linears and travelers, furrow and flood irrigation components, and; tools (Water Tech Ag Supply).

Dealers are formally trained in agricultural engineering or production. Many dealers (and all irrigation manufacturers) belong to The Irrigation Association which "offers a number of certification programs for professionals specializing in agriculture" (Irrigation Association). The Certified Agricultural irrigation Specialist (CAIS) is trained to manage and operate on-farm irrigation systems. The CAIS "understands surface irrigation methods and pressurized systems, including micro-irrigation and sprinklers; evaluates crops and determines water availability and use requirements; understands soil-plant-water relationships and how salinity affects irrigation; selects the most effective irrigation methods and equipment for the application, and develops efficient and cost-effective irrigation schedules that meet the crop's water requirement" (Irrigation Association).

The business model of the irrigation distribution network consists of an exclusive arrangement between manufacturer and distributor such that all products are sold only to the distributor and never to the end-user or grower. Product is sold at a discounted price to the dealer who serves as the wholesaler.

Partnership

The partnership model stipulates that a single irrigation manufacturer identifies a business partner in a particular region and reaches a contractual agreement whereby he/she uses the manufacturers products as the preferential product for irrigation purposes when appropriate. In return, the manufacturer limits distribution of the products within a specific region thereby protecting the interests of the dealer. Typically, the manufacturer supplies in-situ training for the dealer and his/her customers and provides other sales and training tools. This is the model employed by Amiran in Kenya. The Amiran model has increased its scope, now operates in 22 African countries (Kedar, 2013). In the case of Amiran Kenya, a partnership relationship exists with Netafim, and Israeli drip irrigation manufacturer.

It is quite common in the sector of irrigation dealers to start out in the partnership model and then grow into the entrepreneur model.

Collective

The Collective model, in which growers share a common interest or fiduciary relationship and own and operate the irrigation dealership, are common in Eastern Europe and South America. The collective model is also popular among growers in developed countries who have a common contract to provide agricultural products to a firm. For example, Fruit Growers Supply Company is a non-profit cooperative association in the United States that has been providing citrus products since 1907 under the Sunkist name (Fruit Growers Supply, 2013). Fruit Growers Supply purchases their products collectively and covers the operation costs by charging the net cost of products plus 10-percent to its members.

The farmer organizations practicing the Collective model in South America have not institutionalized systems to establish and "understand better the costs and margins along the value chain...(and) do not know how much it costs to provide, for example, technical assistance nor have they incorporated it into their non donor-subsidized cost structures" (Hellin, Lundy, & Meijer, 2007, p. 23). The typical services provided by the collective farmer organizations are: marketing services; facilitation of collective production activities; financial services; technology services; education services; welfare services; policy advocacy, and; managing common property resources (Hellin, Lundy, & Meijer, 2007, p. 5).

The typical famer cooperation model takes place when there is "a match between the existing skills and/or experience of members and what is required to undertake joint activities, internal cohesion and a membership driven agenda; and, successful, commercially oriented, integration of the organization in the wider society" (Hellin, Lundy, & Meijer, 2007, p. 6). This model, therefore, has formal membership requirements, and is not available for all smallholders, in particular, the poorest and least educated. The other potential challenge to the sustainability and efficacy of collective farmer organizations is the dependent relationship that can develop between the organizations and government or NGOs who tend to bail out the organizations when they become financially unstable. This dynamic tends to increase subsidies to the organizations and disassociates it from its market context (Hellin, Lundy, & Meijer, 2007, p. 7).

NGO Farm Center

The Farm Service Center is the fourth agricultural/irrigation model that is differentiated from the other three models by virtue of its lack of irrigation sales capacity, in its current configuration. The objectives of the Citizens Network for Foreign Affairs (CNFA) Farm Service Center, for example, are to "provide technical assistance to existing wholesalers to understand the benefits of quality inputs, improve supply chain management and financial planning, and establish linkages to major international suppliers" (CNFA).

The Farm Service Center input supply model calls for retailers to act as 'one-stop-shops' for local smallholder farmers, demonstrating a profitable business model that is based on a large volume of individually small transactions with small farmer clients. "The CNFA approach to improved access to inputs is coupled with training in business and financial management for input suppliers, as well as expanded extension services for clients on pest diagnosis, input selection and application. Through this model, CNFA facilitates a sustainable commercial relationship between service providers and producers, with profitable and growing farmers becoming repeat, valued customers. By providing technical assistance to existing wholesalers to understand the benefits of quality inputs, improve supply chain management and financial planning, and establish linkages to major international suppliers, CNFA facilitates increased availability and quality of inputs to retailers and smallholders'" (CNFA, 2012, p. 1)

"CNFA's Agrodealer model is aimed at improving farmer incomes and productivity by increasing smallholder access to improved agricultural inputs, especially seeds and better production practices through the strengthening of rural agrodealers. Building a strong network of agrodealers strengthens the overall agricultural sector of a country as these enterprises become centers for input supply, equipment purchase, training and agricultural best practices. CNFA certifies agrodealers after they have completed a rigorous six-module training program covering working capital, inventory control, sales and marketing, record keeping, and managing business relationships. Agrodealers also receive ongoing technical assistance in inputs and equipment, and access to working capital and trade credit through credit guarantees" (CNFA, 2012, p. 1).

Across Kenya, Tanzania, Mali, Malawi and Zimbabwe, over 7,000 Agrodealers have been certified through CNFA's programs and have sold over $170 million in higher quality seeds, fertilizers, and other essential farm inputs. Over 3 million farmers across Africa have benefitted from CNFA's Agrodealer network, resulting in higher yields and incomes; improving food security and nutrition for over 17 million individuals.

The CNFA program is featured in USAID projects—most notably in Ethiopia (USAID, 2013). However, the CNFA model does not provide irrigation equipment or expertise.

Summary

The singular, critical objective for smallholder communities for the next two generations is to increase agricultural production by 100% by implementing sustainable agricultural practices and regimes. This paradigm is successful in developed countries and has not been allowed to function in developing countries. The Development community does not provide epistemic space for the professional agricultural community and does not recognize the criticality of the distribution/grower/manufacturer nexus.

This paper how shown that sustainable agricultural regimes satisfy the two objectives of 1) improving yields and profitability for growers, and 2) mitigating environmental change. This paper has also shown that the key to improving yields involves a myriad of tools, cultivars, and practices that need to be supported on a regular basis by trained distributors. Further, this paper has shown that the current paradigms of the Development community do not provide means and methodologies for improved yields.

This paper has also shown that interventions to repair market failures are not salient for the majority of smallholders in LDCs because the vast majority of production never leaves the smallholder farm. It never enters the market.

Finally, current paradigms of distributor paradigms that function in Least Developed Countries are not fully capable of providing all the irrigation tools and support necessary but further research is needed to determine if they provide a platform upon which all important services can be provided.

Conclusion

The Development community is not the actor that can effect improved agricultural production. Farming is a business and the triangle of stakeholders that is interconnected and financially interlinked consists of the irrigation distributor, the manufacturer and the farmer. The model of the this nexus is the key driver for grower profit in the developed world and it is the basis for further research to determine how best to examine the transferability of that model to LDCs.

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Water for Agriculture, Cities and the Environment: Strategies for Engaging Stakeholders in Cooperative Decision Making

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ABSTRACT

As water is increasingly viewed as a dwindling commodity—not enough for all the uses society has for it—conflict arises. Are there ways to engage stakeholders to transform conflict into cooperation? What are some of the strategies being used? Which ones seem to work best? How could we encourage use of these strategies and experimentation with other strategies?

Introduction

Colorado State University's Colorado Water Institute (CWI) was asked to participate in an effort to engage community members in discussing potential mitigation to reduce opposition to a controversial proposed storage project. CWI believed such an approach would further polarize the community, some of whom staunchly support the storage project and some of who adamantly oppose it. Instead, in an effort to transform conflict into cooperation, they proposed an alternative approach, an educational/action project centered around the Poudre River, which is the root of the storage proposal controversy. Three years later, their project, The Poudre Runs Through It, is proving to be an effective means for building cooperation between agricultural, environmental, municipal, business and recreational interests.

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Background

In 2011, UniverCity Connections, the Community Foundation of Northern Colorado, and Colorado State University's Colorado Water Institute and Center for Public Deliberation joined forces to convene a community series on the Poudre River and the future of Northern Colorado's water. As many as 350 attended the educational and public deliberation sessions. The result was a resounding agreement that those who live along the Poudre and in its valley respect its values of supporting agriculture and urban water use. They love it for its recreational values. But they also want it to be a healthier river. They may disagree on how to get all of that, but they share the common values.

The Colorado Water Institute (CWI) at Colorado State University decided to build on the momentum from the educational series. The result was the convening in October 2012 of a group of 30 leaders from the Poudre's various communities in an eight month process of study and action leading to a series of action initiatives. Participating communities include those through which the river runs through—Fort Collins, Greeley, and Windsor—but also the City of Thornton, fifty miles south, who 30 years ago purchased water rights from a local ditch company with plans to move the water for municipal use through an eventual pipeline.

Participants were chosen for their expertise related to the Poudre River, including those from the agricultural, environmental, municipal, industrial, recreational, business, development, and other sectors. Another factor in the selection of participants was the intent to include individuals associated with the wide diversity of organizations with interests in the Poudre River. These leaders devoted a full day each month to learning from one another and from outside resources in order to build the relationships and the knowledge to come together to identify and develop initiatives. They learned about a number of individuals and groups already working on projects aimed at making the best use of the Poudre River and improving its health—ranging from downtown development to restoration projects.

Let's make the Poudre River the world's best example of a working river that's also healthy

That's the vision adopted by this diverse group of regional leaders as they meet to better understand both the operational and ecological needs of the Poudre River. Sharing their knowledge and experience, this work group learned together about many aspects of the Poudre River to identify opportunities for cooperative action.

In many ways, The Poudre Runs Through It group reflects the diversity of values held by stakeholders in the Poudre. Some value the river mainly as a working river--for agricultural, municipal and industrial needs. Others value its rich recreational opportunities and ecological attributes. But all stakeholders want a river that meets human needs AND is a healthy river in its own right. In the past, these stakeholders too often found reasons not to work together. This group is trying instead to find broadly acceptable ways to meet multiple objectives: to have both a working Poudre and a healthier Poudre. They know the Poudre is a managed river and it is not their goal to return the river to its pre-development condition. They are focusing on areas for mutual gain while not letting divisive issues inhibit their thinking.

After eight monthly all-day meetings in 2012 and early 2013, the group reported on its success so far. They wrote "At times we talked among ourselves and at times we listened to success stories from around the region that provided examples of win-win collaboration. We dealt with the challenge of grasping an understanding of the multiple perspectives/stakes in the river, the challenges brought about by complex legal and institutional realities, as well as the challenges of plans for new diversions. But we also identified a variety of innovative opportunities for voluntary, collaborative solutions that may help protect habitat and water quality while respecting private property rights."

At the close of what they labeled Phase 1, the work group launched a trio of initiatives it believes embody the dual goals of a working river/healthy river. These initiatives are in the incubation stage. Each of them will take a great deal of work and cooperation.

Three Primary Initiatives

The initiatives described below fall under the categories of "Flows, Funding, and Forum." The Poudre Runs Through It will continue to meet with the assistance of the Colorado Water Institute and local funders through at least 2014 to help cultivate these three initiatives and to consider more than 40 other ideas that the group brainstormed. The members of the work group will build on the relationships they have formed—relationships that would have seemed unlikely less than a year before—as they consider additional ideas that may be ready to launch in the future.

FLOWS: Improving the flows of the river while protecting water rights
What would it take to manage the working river system to keep more of the water in the river at critical times and in critical places to begin to improve the river's ecology? Given the large number of agricultural and municipal interests involved, it may be complicated, it may be expensive, and in fact it may prove impossible. Nonetheless, there appear to be at least two distinct approaches to keep more water in the river; both are being investigated. The key to each is using the river, more than canals or pipelines, as a conveyance to move water from upstream to a downstream beneficial use, and moving that water in a way that minimizes losses, does not interfere with anyone's water rights, can be administered under Colorado water law, and is market driven without negatively affecting local economies. In

addition to these two approaches, there may be others that deserve investigation, but these are two that the group is focusing on now. Each of these approaches can benefit the other.

Approach A: Instream flow designation for a section of the Poudre

One way to improve river flows is to officially designate a length of river between specific points as needing a specified minimum flow. Such a minimum flow designation is recognized by Colorado law, established by the Colorado Water Conservation Board in conjunction with Colorado Parks and Wildlife, and water dedicated to such a reach is administered within the state's water right priority system. One such stretch—that could improve both the ecology of the river and its recreational and aesthetic values—could be through the City of Fort Collins. Water leased or otherwise acquired upstream of Fort Collins could then be run through the designated instream flow reach, applied to the beneficial use created by an instream flow right in the designated reach, and used in turn by downstream agricultural or other users. This is a long process with no guarantees, and it would ultimately be expensive. However, if done well, it would protect (and perhaps even improve) the river's diversions for agricultural and municipal use while also helping to protect some of the river's environmental values.

Approach B: Regional Conveyance Cooperation

A second option to use the river as a conveyance may involve regional stakeholders with a need to move water from the Poudre River to other areas for municipal or other uses. For example, cities or water districts that currently divert water from the Poudre River upstream from Fort Collins, or plan to do so in the future could, during certain times or under certain conditions, move all or part of that water further downstream of the Poudre through Fort Collins and perhaps Windsor before diverting it to other uses. Using the river as a conveyance could add water, that for years has been diverted from the river, back into at least a portion of the Poudre. These considerations also figure into trying to develop a win-win arrangement between The City of Thornton and other users as that city gets closer to enacting its plans to move the water it owns south for municipal use. These conveyance enhancement concepts would likely be very expensive for the stakeholders and their ratepayers, and would require a very high level of collaboration, cooperation and public support for successful implementation. But the benefits to the river of such stakeholder collaboration could be significant.

Both Approaches A and B have elements in common. Both would require the replacement, retrofitting, enhancement or construction of major infrastructure such as treatment plants, diversion and head gates, as well as adding telemetered flow measurement. All such changes would be expensive, but doable, and might provide additional benefits such as fish and recreational passage. Both too would require new cooperative agreements among water rights holders to maximize the efficiency of the river—for both working AND healthy river goals.

Flow Education

Any approach to improving flows will involve considerable expense and therefore require public support. Public support can only come through education. Therefore the group has identified as a priority broadening public understanding of key water management concepts. For example, since the right to take water from the river is usually measured in cubic feet per second, it would be helpful to understand just how much a "CFS" really is. Yet few beyond the experts understand flow measurement, and fewer still pay much attention to how much river flows fluctuate through time, or even from place to place along the river. In order to help everyone better understand river flows, a subgroup of The Poudre Runs Through It has imagined a simple but effective project. They will place some attractive flow gages and interpretative signs at strategic places along the river (probably one in Fort Collins and one in Windsor, initially) to help the public visualize flows as measured in cubic feet per second. Sometimes something simple is just what it takes to invoke an "aha" moment.

FUNDING: Translating Vision into Reality
"Putting your money where your mouth is" will be required to achieve the goal of making the working river a healthier river. None of the improvements envisioned will be easy or cheap. They will require engineering and legal fees. They likely will require expensive retrofit of infrastructure and measurement and extensive educational campaigns. They may require lease or purchase of water rights. Finding the money for ventures like these is not simply a matter of a few bake sales or even finding a few well-endowed foundations willing to step up to the plate. Funding the transformation of a working river to a working river/healthy river will require major dollars—public dollars. The Poudre Runs Through It has undertaken an initiative to investigate how such funding could be generated. They will look at successful models, such as Larimer County's Open Space Tax or the state of Colorado's GOCO fund, and others, for inspiration. They believe that those who live in the Poudre River Basin will respond enthusiastically to this vision. Studies show that most everyone loves and benefits from the Poudre. They want it to continue providing for their agricultural, urban, and recreational needs. But all of them want the river to be healthy and clean, and that all takes money.

FORUM: Convening for Cooperation
Another initiative will be the establishment of an annual Poudre River Forum to bring together all the communities that benefit from the Poudre to celebrate and cooperate. A one-day gathering will feature presentations and panels, think-tank topics, and fun. The purpose of the forum is to convene the wide diversity of those who care about the river to collaborate on how they can meet the dual goals of working river/healthy river. A subgroup is now planning for the first Forum to take place early in 2014. What's the scope of this vision? At least 300 people -- maybe as many as 500 -- meeting annually to strategize for a healthier working river.

Conclusion

As the gap between water supply and demand increases throughout not only the arid western United States but elsewhere throughout the country and the world, conflict is sure to increase. Strategies to bring together diverse groups with diverging interests are needed. In this case, a neutral entity—the Colorado Water Institute at Colorado State University—sought to build on the common values of diverse stakeholders to build relationships and multiple benefit initiatives that can make a significant contribution toward fulfilling those common values. The debate about building new storage has not disappeared, and it will not. But a strong group of stakeholders has broadened its understanding of the underlying and broader issues of which the storage debate is only one part. These stakeholders are leaders in their communities and have already influenced a more finely nuanced conversation about the Poudre River. And more, they have launched concrete initiatives which have the backing of groups such as farmers and environmentalists who have traditionally been at opposite ends of a polarized debate. Further experimentation with collaboration building strategies such as this is needed.

The Wide World of Water Metrics

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Abstract. *There is growing public awareness of the world's limited water resources and most sustainability organizations include some type of water metric when evaluating the environmental impact of consumer products. Commonly used approaches typically fall into three categories: 1) water scarcity models; 2) water footprints; and 3) life cycle assessment (LCA) techniques. Measures established by the irrigation community are typically not utilized although irrigation is most always listed as the largest water use component in the water footprint of any agricultural-based product. This is because these metrics focus solely on water consumption (removal of water from the watershed) and ignore total water withdrawn (water removed including that returned to the watershed, as in power generation, for example). Results based on water metrics that do not take into account the critical nexus between water and power generation tell an incomplete story and could underestimate the water risks for companies whose products are based on energy intensive processes. Some newer approaches, usually coupled with LCAs, are starting to broaden the water dialogue. For instance, some metrics attempt to estimate the impact of water use on human health by attributing loss of water to malnutrition, thus acknowledging the importance of irrigation for food production. Because purchasing and product design decisions of brands and retailers are starting to be driven by the metrics adopted or developed by sustainability initiatives, accuracy and inclusion of context around agricultural water use is critical. There is a pressing need for those with expertise in agriculture and irrigation to become engaged in the evaluation and development of these metrics. The irrigation community is well-positioned to ensure that the complexity of agricultural systems is captured by those developing water metrics and that these same entities are informed about solutions for managing this increasingly limited resource.*

Keywords. Sustainability, life cycle assessment, water footprint

Introduction

It is clear fresh water will become scarcer in many parts of the world as the population grows over the next 40 years. The pressure on water resources is already evident in the decline of many aquifers across the United States as recently summarized by Konikow (2013). Very few environmental impacts are as complex and emotional as water resources. Water is a human necessity, a commoditized resource, an ecosystem matrix, a geochemical cycle, and of cultural/spiritual value, all at the same time. Water scarcity threatens the safety and stability of consumer supply chains, especially food, fiber, feed, and fuel. This has led a number of companies to evaluate water use across their supply chain and a corresponding increase in methods to quantify, either on an absolute or relative basis, the water associated with raw materials and processes throughout the life of a product. Some approaches only consider water consumption (water removed from it source watershed either by evaporation or embedded in the product) and may not consider site-specific water availability. Essentially all of the approaches identify irrigation water as a major contributor for any agriculturally-based product. Without the benefit of additional context, this can be misinterpreted to mean that water use for irrigation is wasteful and therefore undesirable.

The objectives of this paper are to: 1) review current sustainability efforts and metrics as they pertain to agricultural water; and 2) to inform the irrigation community of these efforts so we can enter into a constructive dialog on how irrigation water use should be assessed. The first section of this paper reviews several water metrics with special emphasis on those applied in sustainability discussions and then provides an overview the major sustainability organizations that are using water metrics in their programs. The last section will focus on many of the complexities related to irrigation water use that are not addressed by these metrics.

Water Metrics

Developing metrics for the critical dimensions of water requires agreement on what those dimensions are. There is general agreement that scarcity and water quality are metrics of concern. Both of these metrics are dependent on geospatial and temporal resolution. Water scarcity may be chronic or seasonal, regional or local, depending on the characteristics of each place. This section will briefly review irrigation performance measures and then follow with water metrics applied to product evaluation and sustainability discussions in three categories: 1) indices used to more generically rank levels of water scarcity; 2) the concept of a "water footprint"; and 3) water metrics used in life cycle assessments (LCA). Each category has different strengths and weaknesses, and all are constantly being refined and improved.

Established Irrigation Water Metrics

Over the last 50 years or more many measures to assess the performance of irrigation systems at different scales have been developed. An effort to standardize these measures, reported by Burt et al. (1997), was in part motivated by water rights and regulatory discussions. The hope was to standardize the definition for many key irrigation performance indicators including: irrigation efficiency; distribution uniformity; and application efficiency. The authors also made the point that some measures can be applied across different spatial scales and may encompass different time intervals, while others may only apply to a specific irrigation event in one field. For example, a key measure used in evaluating agricultural water use is irrigation efficiency (IE), defined by Burt et al. (1997) as:

$$IE = \frac{Volume\ Irrigation\ Water\ Beneficially\ Used}{Volume\ Irrigation\ Water\ Applied - Change\ in\ Storage\ of\ Irrigation\ Water} X100\%.$$

To illustrate the relevance of spatial scale for IE, consider the case when tail water leaves a field, it may not be considered beneficially used at the field scale; however, if that tail water is diverted to another field it would be considered beneficial at the farm and district scales. Jenson (2007) provides a detailed discussion of irrigation efficiency, including misinterpretations of the term, especially the incorrect concept that improving irrigation efficiency at the field scale *must* result in increased water availability at the watershed scale.

To overcome some of the limitations of the term irrigation efficiency, Solomon and Burt (1999) discuss the term “irrigation sagacity” (IS) in an attempt to describe not only beneficial water use, but also “reasonable” water use. Mathematically it is similar to equation 1, but adds “or reasonably” following “beneficially” in the numerator. Figure 1 illustrates the difference between IE and IS.

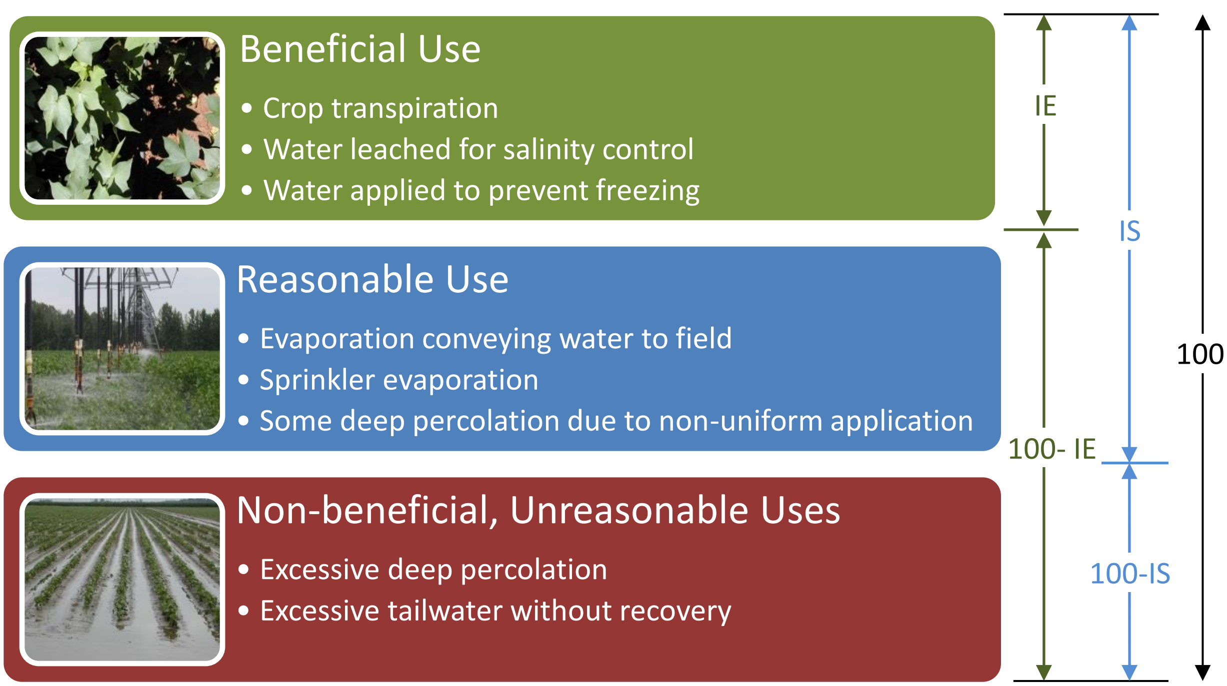

Figure 1. Comparison between irrigation efficiency (IE) and irrigation sagacity (IS). (Adapted from Solomon and Burt, 1999).

Another key concept in evaluation agricultural water use is the mass of economically valuable material produced per volume of water used. Historically this was often referred to as “Water Use Efficiency” (WUE), but as with irrigation efficiency, the quantification of WUE requires a definition of scale. Howell (2001) reviews several forms of WUE definitions, where the numerator is typically economic yield, but how the “water used” is determined varies. Howell (2001) also reports on an irrigation water use efficiency (I_{WUE}):

$$I_{WUE} = \frac{(Irrigated\ Yield) - (Non - Irrigated\ Yield)}{Irrigation\ Applied}$$

More recent literature (e.g., Zwart and Bastiaanssen, 2004) has adopted the term “Crop Water Productivity” (CWP, kg m^{-3}) defined as:

$$CWP = \frac{Marketable\ Crop\ Yield}{Actual\ Seasonal\ Evapotranspiration}$$

These metrics reflect a return-on-investment approach to efficiency. They are useful for comparative assessment of water use at the enterprise level (maximum potential gain by cropping system for available resources), within a region (which production strategies give greatest yields for a cropping system), or across regions for a given production system. These metrics can help identify opportunities for increased efficiency. However, they do not address competing demands associated with scarcity, or impacts associated with runoff or infiltration. The challenge of defining “simple” irrigation performance parameters provides evidence that any effort to quantify water metrics for an agricultural system is not trivial.

General Water Scarcity / Stress Indices

Several approaches to quantifying water scarcity such as the Palmer Drought Index (Palmer, 1965) which addresses short-term climate water limitations and the Falkenmark indicator (Falkenmark, 1989), an index that considers population demands and availability of local water resources in the long term, have been developed over the last five decades. The current trend in quantifying water stress in regions is to move beyond a simple water balance and also consider impacts on water quality and the economic and social capacity of the region to adapt to water shortages (e.g., Ohlsson, 2000). Brown and Matlock (2011) provide a review of many water scarcity indices and, in that review, divide scarcity indices into three categories: 1) indices based on human water requirements; 2) those based on water supply; and 3) indices incorporating environmental water requirements.

With regard to human requirements, Figure 2 illustrates the distribution of basic human water needs from Gleick (1996) as summarized in Brown and Matlock (2011). The total estimate is that at least 50 liters per person per day is needed to meet direct basic human water needs (that is, water delivered directly to a person). In addition to direct water use, a United Nations reports data indicating that 2000 to 4000 liters of water per day are needed to supply a person’s food requirements (UN, 2013). The fact that water associated with a person’s food requirements is almost 100 times their direct water needs is a clear indication that the biggest societal impact of future water shortages will be related to meeting nutritional requirements.

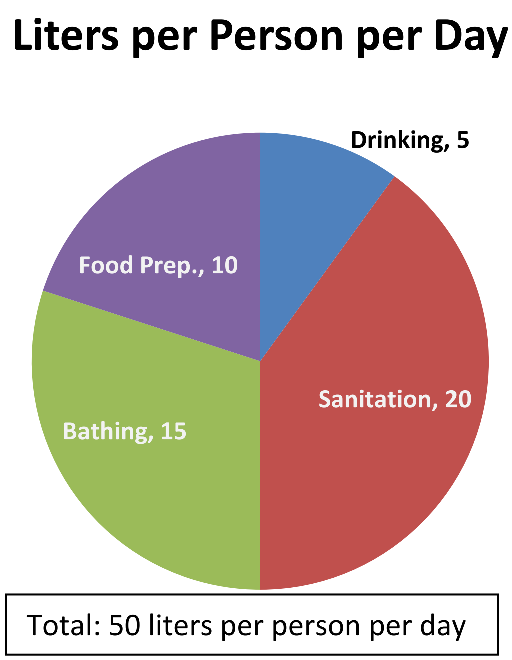

Figure 2. Basic human direct water needs.

One current tool used to estimate water risk is provided by the World Resource Institute's Aqueduct (http://aqueduct.wri.org/). The tool provides a number of metrics, including the "baseline water stress" (BWS) shown in Figure 3. It is defined as the total water withdrawn as a percent of total annual flow (Gassert et al., 2013). The BWS is one of twelve water indicators computed on a global basis and available from the Aqueduct web site. The concept is that companies can use these indicators to identify areas in the business supply chain with high water risk and provide guidance to investors on their water readiness plans (Reig et al., 2013). Reig et al. (2013) divide water risk into three categories: 1) Physical Quantity (lack of water); 2) Physical Quality (impacts on water quality); and 3) Reputational (if a company's product is deemed to negatively impact water resources, the brand is threatened).

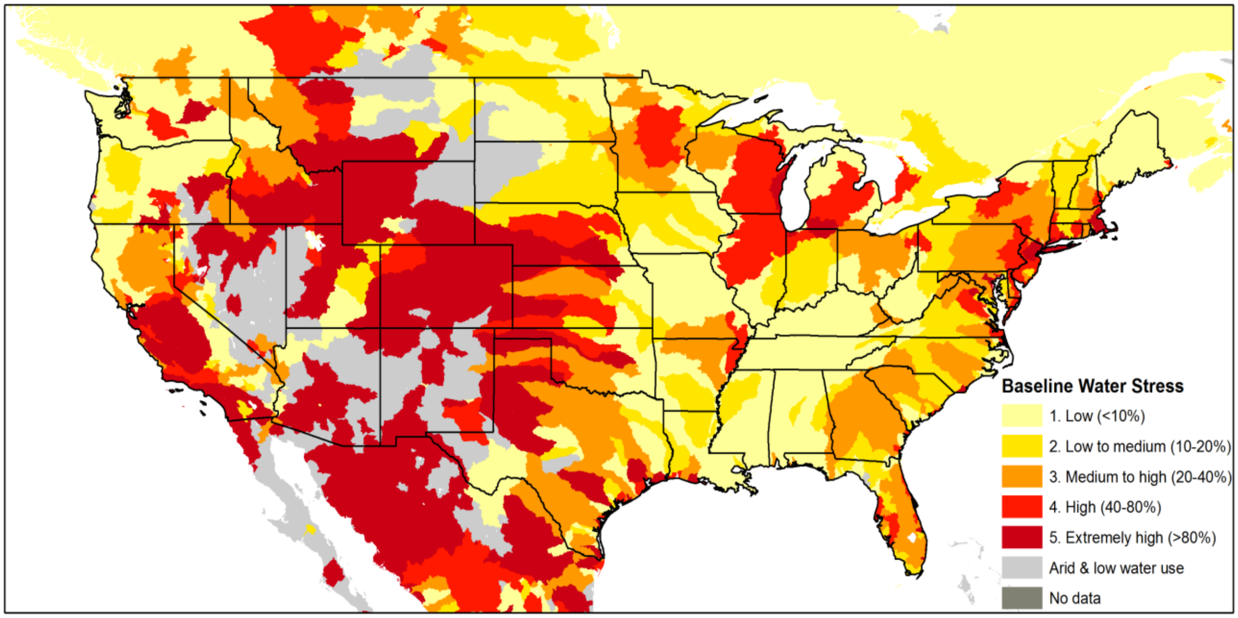

Figure 3. Baseline water stress from WRI's Aqueduct (Gassert et al., 2013).

Another term used in water resources discussion is "water security." The United Nations currently defines water security: *"as the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability."* (UN, 2013). The same UN report acknowledges the tight linkage between water, energy and food.

Water Footprints

The concept of a water footprint is similar to (and essentially derived from) an ecological footprint; and one of the first uses was introduced in the discussions of virtual water by Hoekstra and Hung (2002). For the purpose of this paper, the water footprint definition will be based largely on the definitions provided by the Water Footprint Network (www.waterfootprint.org). A recent review of the evolution of the water footprint is provided by Chapagain and Tickner (2012).

A goal of the water footprint concept is to raise awareness and to quantify all of the water *consumed* in the production of a product, or in some cases water consumed by groups or nations. Because the focus of the water footprint concept is on consumption, with the exception of a rough estimate of the impact of water pollution associated with a product, issues arise when comparing products such as apparel that are derived from both agricultural and synthetic raw materials. For example, by definition, water consumed is water that has been taken from one watershed yet returned to another. The water applied to crops through irrigation is considered water consumed since the water may no longer be available within that watershed. However, no consideration is given to the fact that the water that might return as rainfall to the same watershed. In contrast, the vast amount of water associated with power generation is largely ignored since most of the water used for power generation is returned to the same watershed, albeit of a different quality. Kenny et al. (2009) reported that water for thermoelectric power generation was 51% of all water withdrawn in the United States in 2005, followed by irrigation at 31%. With a focus solely on water consumption, the water footprint of an agricultural product will always be greater than that of a product derived from a synthetic raw material even though vast amounts of energy are required for the production of the synthetic product. Hence, a methodology based solely on water consumption will not capture all of the water resource needs of a product, especially those dependent on energy intensive processes.

The water footprint is broken down into three major components:

1. **Green** water consumption – water that originates directly from soil moisture derived from rainfall.
2. **Blue** water consumption – water that is diverted from rivers, lakes, and groundwater. Note that recycled water (e.g., use of effluent for irrigation) still counts as blue water use in a water footprint.
3. **Grey** water – volume of water in the creation of a product that would be needed to dilute any pollution to an established concentration accounting for the background concentration at the point of emission.

The water footprint assigns equal weight to green and blue water even though they are tracked separately. The water footprint of a product is often report as a total of the three categories, so the portion of water in an agricultural commodity from rainfall is not always apparent. For crops, the mass produced per evapotranspiration over the time span of production (a single growing season in the case of crops, or years of growth in the case of forestry products) is used to define total water use. While a direct measure of crop water use efficiency is ideal, such data is not always available on a site-specific basis and the CROPWAT program (FAO, 2010) is recommended by the Water Footprint Network for calculating water use at regional levels.

Ridoutt and Pfister (2012) have proposed a different methodology to allow water pollution to be included in a single score measure of water use by adapting life cycle assessment methodologies, as opposed to the Water Footprint Network approach. The resulting water footprint is referred to as "H_2Oe", i.e., water equivalents in the same manner used for reporting greenhouse gas emissions in terms of carbon dioxide equivalents.

In addition to work by the Water Footprint Network, the International Organization for Standardization (ISO) is drafting Standard 14046 – "Principles and Guidelines for Water Footprinting" (ISO, 2013). The Draft International Standard follows closely the same requirements set forth in the standards for life cycle assessment. Water footprint may be integrated with LCA or may be a standalone assessment. The requirements include defining the goal and scope, developing a water footprint inventory analysis and conducting an impact assessment with subsequent interpretation of the assessment. There is geographic and temporal specificity, and all environmentally-related aspects of environment, human health and resources are considered, although economic or social impacts are not considered. The pressure on water availability and the impacts related to water degradation are assessed. If only one impact is studied then the term water footprint should be qualified, e.g., water acidification footprint or water scarcity footprint. A water footprint profile is compiled from all of the indicators chosen in the goal and scope. This profile can be aggregated into a single score, but the single score cannot be used for comparative public assertions.

Life Cycle Assessment Water Metrics

Life cycle assessment (LCA) attempts to track multiple environmental impacts of a product from its production, including raw materials, through consumer use to disposal. The ISO 14040 series of standards for Life Cycle Assessment define the processes needed to conduct an LCA for a specific product (ISO, 2006a and 2006b). Historically, LCA methodologies were more focused on water quality impacts. Many life cycle inventories included total water withdrawn but did not distinguish between consumptive versus total use. More recently, life cycle inventory (LCI) software began to include water consumption, for example, in GaBi with the release of version 5 (GaBi, 2011). In contrast to water footprints, most LCA methodologies do not include rainfall (green water) in either water consumption or water use. Most of the popular inventory databases are inconsistent in the type of water that is tracked. For example, Kounina et al. (2013) note that of the most common LCA databases only one considers evaporation from reservoirs. This is, however, being addressed in the water footprint ISO standard.

The difference in water consumption versus total withdrawn from an LCA perspective is illustrated in Figure 4 for a knit shirt using data from Cotton Incorporated (2012). In that study, the shirt's life cycle was divided into three major phases: 1) agricultural (agricultural production to ginning); 2) textile production (fiber to fabric); and 3) use (cut and sew plus consumer use including washing and drying). From Figure 4 it is clear that the agricultural phase dominates the amount of water consumed, but the textile production and consumer use phases are larger when considering total water withdrawn ("withdrawn" in is sometimes referred to as "water used" in LCA reports). The major reason for the difference is that water withdrawn includes water for power generation, and these two phases had much greater energy use than the agricultural phase.

Another point illustrated by Figure 4 is the concept of "direct" and "indirect" water use. For example, water diverted to a textile mill for fabric dyeing is direct water use while the water supplying the power plant that provides electricity to the mill (assuming it is off-site) is indirect. Both consumptive and water withdrawn can be categorized into direct and indirect uses. Therefore, a product that is derived from an energy intensive process may have a high level of water withdrawal from an LCA perspective although there may be very little actual water use at the manufacturing facility.

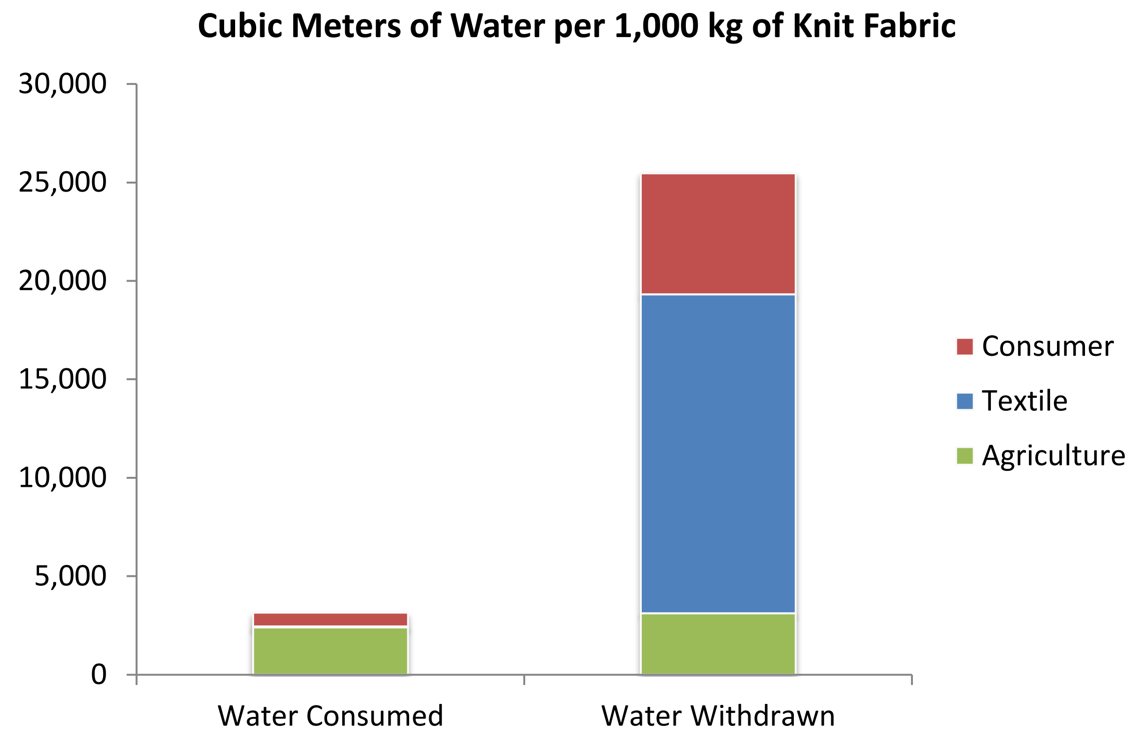

Figure 4. Comparison of water consumed and water withdrawn based on the LCA of a knit shirt from Cotton Incorporated (2012).

The distinction between LCA water-consumption and water-withdrawn metrics illustrate an important point in assessing the water risk in a product's supply chain. If only consumption is considered, products based on synthetic inputs may falsely appear to have low water risk. For example, if a synthetic product relies on energy intensive manufacturing processes, and the water that is supplying the power plants that are providing that energy becomes limited, there is a risk to the supply chain due to disruptions in water supplies (Webber, 2012).

There are now efforts in the LCA community to go beyond accounting for the volume of water consumed or withdrawn by also considering the impacts of water availability in the region where it is used. For example, Pfister et al. (2009) estimates the impact of freshwater consumption on human health by predicting malnutrition caused by reduced food availability due to the diversion of water away from agriculture. They also have two additional impact indicators: ecosystem health impacts are estimated by assuming a loss of biodiversity as water becomes scarce in the region; and a resource depletion indicator, a calculation based on the energy it would take to replace the blue water consumed by the desalination of seawater.

Boulay et al. (2011) also have proposed a methodology for LCAs that predicts the impact of changes in water availability on human health at a regional level. It has been used to create a water stress index that is integrated as part of a new LCIA methodology referred to as "IMPACT World+" (see http://www.impactworldplus.org/en/index.php). The Boulay approach defines different water uses (e.g., domestic, agriculture, power) and 17 water categories that are related to the source of water (surface, ground, rain) and the quality of that water. The impact on different users in the region is determined by their upstream or downstream relationship to the water withdrawal and impacts take into account an area's economic status (assumes low income areas will experience the impact of water deficits, while high income areas can compensate for water loss). The method also calculates a human health impact related to malnutrition due to decreased agricultural productivity from lack of water. The method assumes water scarcity occurs mostly due to water consumed although there is some accounting the loss of functionality of degraded water returned to the system for specific user categories.

The models of both Pfister et al. (2009) and Boulay et al. (2011) utilize data from the Water Global Assessment Prognosis 2 model (WaterGAP 2, Alcamo et al., 2010). The WaterGAP 2 model attempts to estimate water availability within a river basin and also models the water use from all sectors (industrial, municipal, agricultural) in the basin. For domestic water use, "domestic structural water intensity" (m^3 per person) is defined as a function of the gross domestic product (GDP) of a region assuming water use increases with GDP. Industrial water intensity is also related to GDP and is assigned units of m^3 per MWh. The method also includes the ability to make adjustments for technology changes that will improve water use efficiency. Agricultural water use is focused on water drawn for irrigation which is considered to be consumed (evaporated). The irrigation model is based on Doll and Siebert (2002) and assumes crop water needs will be met; it does not account for situations where deficit irrigation may occur due to limited water resources. The net irrigation is computed as the difference between crop demand estimated from a crop coefficient approach, and precipitation. The water supply is based on a global hydrology model that conducts a daily water balance on a regional basis.

An example of the water stress classification from the WaterGAP 2 model for the continental United States is presented in Figure 5. In general, the areas listed as having some level of stress correspond to areas of lower annual rainfall with the exception of the state of Florida and the mountains of California (see Figure 6).

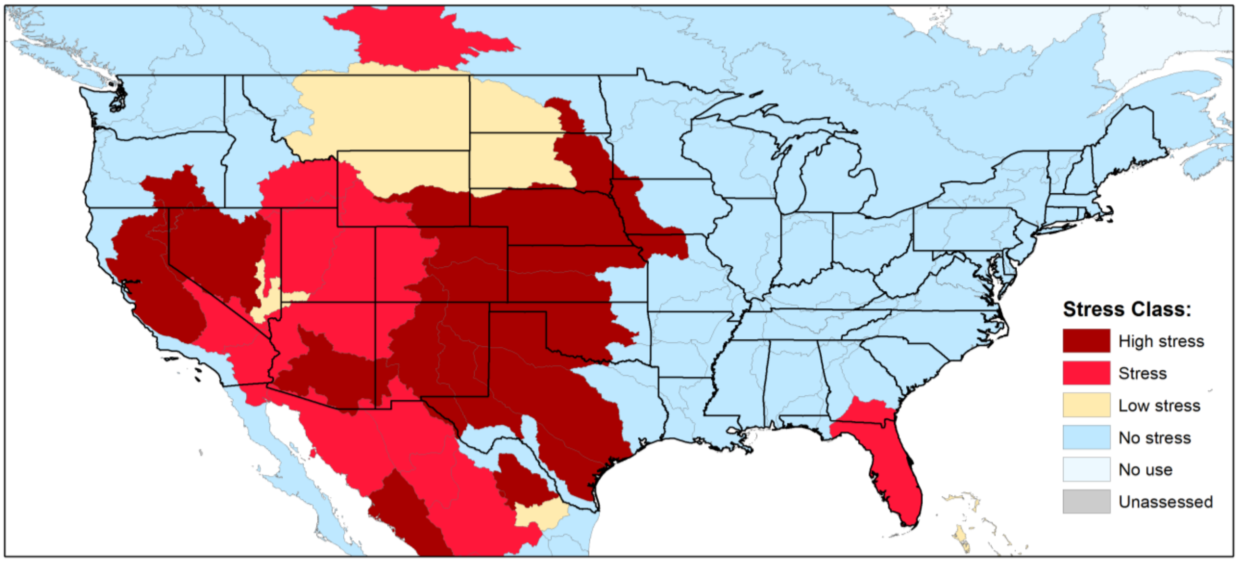

Figure 5. Degree of water stress by freshwater eco-region – derived from data of Alcamo et al. (2010) as prepared by the Nature Conservancy and accessed through ArcMap 10.1 (ESRI, 2012).

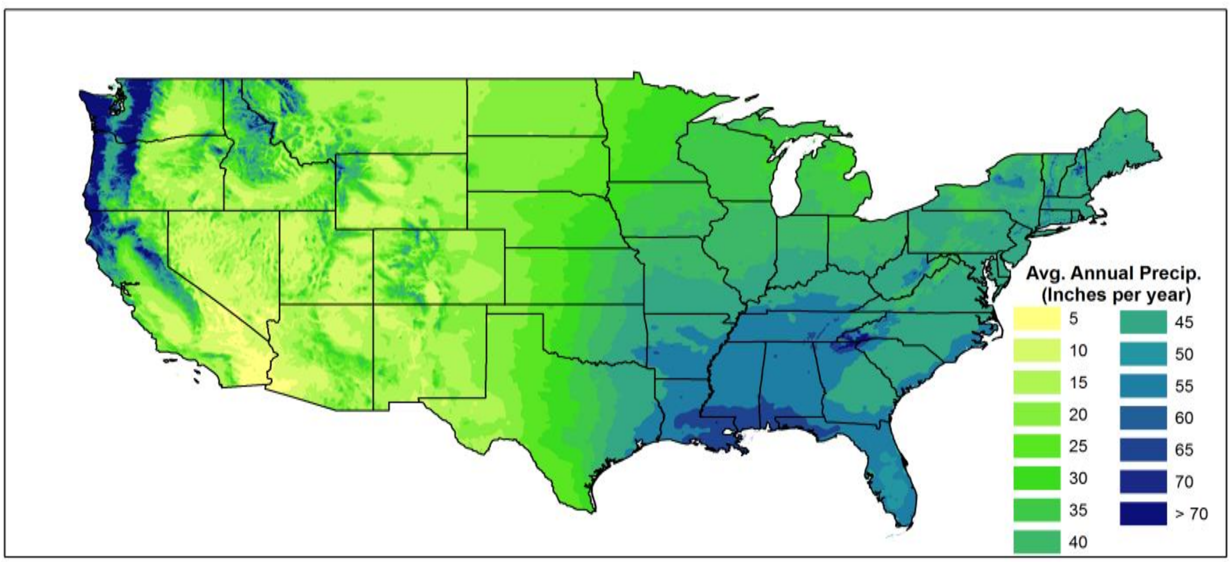

Figure 6. Average annual rainfall from 1961 to 1990. Derived from data provided by the USDA-NRCS National Cartography and Geospatial Center.

There is now an effort among those in the life cycle assessment community to build consensus on what characterization methods should be used for LCA through an international group referred to as WULCA (http://www.wulca-waterlca.org/). The group is part of the United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative. As part of that effort, Kounina et al. (2013) published a review of current LCA approaches and attempted to define the attributes a system should have in order to address the impact of fresh water use in LCA. They concluded there is a need to track water based on its origin (surface, ground or precipitation stored as soil moisture) and that assessments need to be done at a regional level due to the geographic variability in water scarcity.

Because water scarcity and end-point impacts such as those on human health are built into LCA metrics, the complexity of the models and their associated uncertainty is increased. As seen in the previously described examples, the attempt to quantify the complexities of water availability at small regions on a global basis requires many assumptions and estimates. And many of these estimates are not only related to hydrologic parameters, but also to socioeconomic information.

Sustainability Efforts and Water Metrics

There are a significant number of global efforts aimed towards quantifying or certifying the "sustainability" of a product or supply chain. Some are based on prescribed practices while others are focused on the development of ways to measure sustainability. This section reviews some of the initiatives that include agricultural products and that use water as one of the measures of sustainability. Note that many of the organizations using water metrics have key members whose decisions could have a major impact on agricultural supply chains.

CEO Water Mandate

The CEO Water Mandate was started in 2007 by the United Nations Secretary-General to help companies develop and disclose sustainable water practices and policies (http://ceowatermandate.org/). Companies that commit to the mandate agree to conduct a water use assessment, set targets for water conservation, invest in water conserving technologies, and consider water sustainability in their business decisions. The organization suggests several potential tools a company can use for self-assessment, including water footprints and LCA. They also recommend other tools such as The World Business Council for Sustainable Development's (WBCSD) Global Water Tool (GWT, http://www.wbcsd.org/work-program/sector-projects/water/global-water-tool.aspx) that focuses on assessing water scarcity risk on a site-by-site basis. The tool uses an Excel spreadsheet to collect data on water use for each site in a supply chain and shows the water metrics associated with those sites. It also allows the sites to be shown on a map, and the map is coded based on different water metrics such as availability and stress. The GWT is integrated with the "Local Water Tool" (LWT) developed by Global Environmental Management Initiative (GEMI). Data from the GWT can be loaded into the LWT for more location-specific risk, impacts and management of water use and discharge.

Sustainable Apparel Coalition

The Sustainable Apparel Coalition (SAC, http://www.apparelcoalition.org/) "is an industry-wide group of over 100 leading apparel and footwear brands, retailers, suppliers, nonprofits, and NGOs working to reduce the environmental and social impacts of apparel and footwear products around the world." Members include Nike, Adidas, Puma, Gap, REI, Coca-Cola, Hanesbrands, Levi's, JCPenney, Target and Walmart. A significant outcome of the SAC's efforts is the Higg Index which is a still-evolving Excel-based tool designed to enable the apparel industry to evaluate the sustainability of their supplier facilities, products, and specific brands. Currently, the indicator questions within the Higg Index are qualitative measures of company actions in various areas of the supply chain. Water use and water quality are addressed in the facility module by asking whether the facility measures water use and whether goals are set or plans exist for water reduction. Similar questions are asked about wastewater discharge, treatment, and reduction. In the brand and product modules, questions are focused on encouraging brands to better understand the water requirements of their supplier's manufacturing equipment and processes, chemical use during manufacturing, the environmental profile of raw materials and the design of products that require less water or less polluting chemistry during manufacturing. The questions are assigned points and are designed within a framework in which more responsible choices result in higher scores.

Future versions of the index may be based on more quantitative, LCA-type measurements. Another significant effort by the SAC has been the development of guidelines for apparel ecolabels. The guidelines, called Product Category Rules (PCR's), is a like a recipe for creating an Environmental Product Declaration's (EPD), which is essentially an ecolabel. EPD's and ecolabels are common in Europe and are currently voluntary but will become mandatory in the coming years. The water-related impacts currently required by the SAC's PCR for apparel products are water depletion and eutrophication. This could change in future versions of the PCR or for specific product categories if the ISO standard 14046 is adopted or if other LCIA methods for measuring water become accepted.

The Sustainability Consortium

The Sustainability Consortium (TSC) is another industry organization that is taking a metrics-based approach towards driving sustainable practices (http://www.sustainabilityconsortium.org/). The scope of TSC includes a broad range of product categories that include food, beverages and agriculture; textile and clothing; electronics; toys; health and beauty products; and paper, pulp, and forestry. The range of categories results in a diverse membership including brands and retailers such as Best Buy, Dell, Disney, Proctor and Gamble, Walmart, Tyson, Smuckers, and McDonalds, as well as agribusiness and chemical companies such as Syngenta, Bayer CropScience, BASF, DOW and Monsanto. A number of NGO's such as World Wildlife Fund (WWF), Environmental Defense Fund (EDF), The Nature Conservancy (TNC) and the Natural Resources Defense Council (NRDC) are also represented. The Food, Beverage and Agriculture (FBA) sector is the largest sector in TSC with 26 current product categories. Recently, TSC has compiled several products into one category, e.g., milk, cheese, butter, and yogurt under Dairy and beef and pork into Livestock. Cotton holds a spot in both the FBA and Clothing, Footwear and Textiles (CFT) sectors. Figure 7 is a representation of the current categories listed under FBA.

Figure 7. TSC Food, Beverage and Agriculture categories as of August 2013 (from: http://www.sustainabilityconsortium.org/product-categories/).

The TSC's primary product has been the development of a Sustainability Metric and Reporting System, or SMRS, a process designed to provide retail buyers with a mechanism in which to compare and choose suppliers based on environmental and social performance. The SMRS is comprised of "knowledge products", documents containing product- or commodity-specific information derived from literature and research reports. With member input, environmental and social hotspots and improvement opportunities are identified and Key Performance Indicators (KPI's) are eventually developed. The KPI's are sets of questions that retail buyers can use to start a sustainability discussion with a supplier, or a retailer may also opt to use the KPI's as a supplier scorecard. Like SAC, the KPI's are designed to be a tiered point system in which the more environmentally- and socially-responsible suppliers are rewarded with higher points. In the textile sector, water is a hotspot on the farm, in manufacturing, and in consumer use, so several or more KPIs have been drafted to address each of these areas of the supply chain and to determine a supplier's progress on reducing water use and improving water quality. (The textile sector is a recent addition for TSC, so the number of KPIs has not been finalized.) In the FBA sector, several KPI's relate to on-farm water use. Irrigation is designated as a hotspot for all food, beverage and commodity products although the response options are designed to capture irrigation optimization strategies that a grower might implement. Water scarcity and sourcing questions related to water scarce regions are listed as separate KPI's. To encourage change throughout the supply chain, apparel suppliers to Walmart, for instance, are expected to either know, or be involved in an initiative that does know, about the percentage of cotton farmers who track on-farm irrigation water use, for example. TSC recognizes that a typical apparel manufacturer does not have this information but is asking the question to encourage dialog between the manufacturer and the farmer. Likewise, a KPI about water scarcity expects the supplier to know whether and what percent of their raw material is sourced from a water scarce region. A list of tools for measuring water use is provided in the additional guidance that accompanies the KPI's. A challenge that both the SAC and TSC face is whether these systems will actually drive enough change to have impact at the natural resource level.

Carbon Disclosure Project – Water Risk

The Carbon Disclosure Project (CDP) water program encourages companies to evaluate and report the water risk across their supply chains (https://www.cdproject.net/water). The goal of the project includes creating better access to corporate water data to allow better decision making, and accelerate the development of standard water metrics. In 2012 more than 50% of the 191 companies responding to their questionnaire indicated negative impacts on their business due to water issues (CDP, 2012). In 2012, companies reported 470 investors supported their information request.

Sustainable Agriculture Initiative (SAI)

SAI is an organization started by Nestlé and Danone to support the development of principles and practices that form the basis for different agricultural production systems (see http://www.saiplatform.org/) on a global basis. The current water focus of that effort is centered on farm level practices (SAI, 2010); however, they are piloting a Water Impact Calculator. The SAI does appear to have an interest in the water footprint approach of Hoekstra and Hung (2002), but also point out some of the shortcomings of the methodology including the lack of rigor in estimating "grey" water for agriculture, and that often water requirements are calculated based on the assumption that all crop water needs are met (SAI, 2009).

The SAI water focus includes both quality and quantity. To address the quality aspect, SAI encourages approaches such as integrated pest management (IPM) and conservation tillage. For some of the performance indicators they do recommend the use of distribution uniformity (after of lowest quarter divided by average of all catch cans); and metering water delivery systems.

Field to Market (FTM)

Field to Market (www.FieldToMarket.org) is an alliance, across the agricultural supply chain, of organizations who have adopted an outcome-based approach to evaluate progress towards sustainability. A large part of the effort is to use publicly available national data to track several environmental indicators for major crops over time. Water-related measures include an estimate of soil erosion from RUSLE2 and a water quality index (WQI) developed by the USDA, NRCS. The FTM report includes trends in total water used for irrigation, and the primary metric is an estimate of the amount of yield increase attributed to the use of irrigation per unit of irrigation applied, very similar to Irrigation Water Use Efficiency metric previous noted from Howell (2001).

Challenges to Interpreting Water Metrics for Policy and Product Decisions

While considerable effort has been devoted to defining water metrics and a number of organizations are attempting to use these metrics as part of their sourcing decisions, there is a real possibility that the complexities of agricultural systems could to lead poor decision-making. For example, McGuire (2011) documents the decline of the Ogallala Aquifer in the central United States over the last 50 years. It is clear that sections of the Ogallala, particularly in western Kansas and the Texas Panhandle, do not receive significant recharge and will eventually be depleted. The water metrics and certification systems that consider regional water stress will score all crops and manufacturing processes in this region poorly. However, crops like cotton and sorghum are already predominately grown without irrigation. Thus, when the aquifer is depleted, these crops may well present the only sources of income for farmers in the region. It seems illogical and punitive, then, to score these crops poorly based solely on a regional water stress metric.

Another challenge is the definition of “consumption” as water leaving a watershed and the classification of irrigation water as being water consumed. Lo and Famiglietti (2013) have demonstrated that the increased evapotranspiration due to irrigation in California’s Central Valley increases precipitation over the Colorado River Basin, corresponding to an approximately 30% increase in the stream flow of the Colorado River. So, while it is true that a portion of irrigation water evaporates, not all of that evaporated water meets the technical definition of “consumption” since part of that water falls back as rainfall into the hydrologic basin of origin.

Another issue in many of these metrics is the uncertainty surrounding the estimate is either not reported or is extremely high. For agriculturally based products, a more robust approach may be to use a reported value of the crops’ crop water productivity (CWP) to estimate the water used in its creation. For example, Zwart and Bastiaanssen (2004) conducted a global literature review of the CWP for several crops, including cotton. In the data reported for seed cotton (fiber + seed), the CWP was reported with a mean of 0.65 kg m^{-3} with a standard deviation of 0.23 kg m^{-3} and coefficient of variation (CV) of 35%. The mean value is equivalent to 1.53 m^3 of water per kg of seed cotton. This is in contrast to Chapagain et al. (2006) who compute a global average water foot print of 3.6 m^3 per kg of seed cotton (essentially split between green and blue water), twice that of Zwart and Bastiaanssen (2004). While no statistic on the variance in their data is directly report, the tabular data suggest the standard deviation for values reported by country is on the order of 2.1 m^3 kg^{-1}, resulting in a CV of 58%. Chapagain et al. (2006) also report an allocation method to assign water to the fiber and seed; however, even after that allocation method, there estimate of the fiber water footprint is still twice that reported by Zwart and Bastiaanseen (2004). More work is needed to determine what method will best minimize the uncertainty in crop water use / footprint estimates. Without quantitative uncertainty water footprint data are simple anecdotes, and useless for informing better decision making with regards to water use allocation and conservation.

A final challenge to characterizing the water impact of agricultural products is the need for timely data. As shown in Figure 8, crop yields in the United States increase at a steady pace, and these yield increases have come without increased water use on a per acre basis for all of the crops shown from 1980 to 2011 with the exception of wheat which had a small (6%) increase (Field to Market, 2012). Much of the yield increase is driven by improved crop varieties from traditional breeding, better crop management, and in the case of corn, cotton, and soybeans, biotechnology. Therefore, any metric used to quantify products derived from agriculture should be updated at five year intervals.

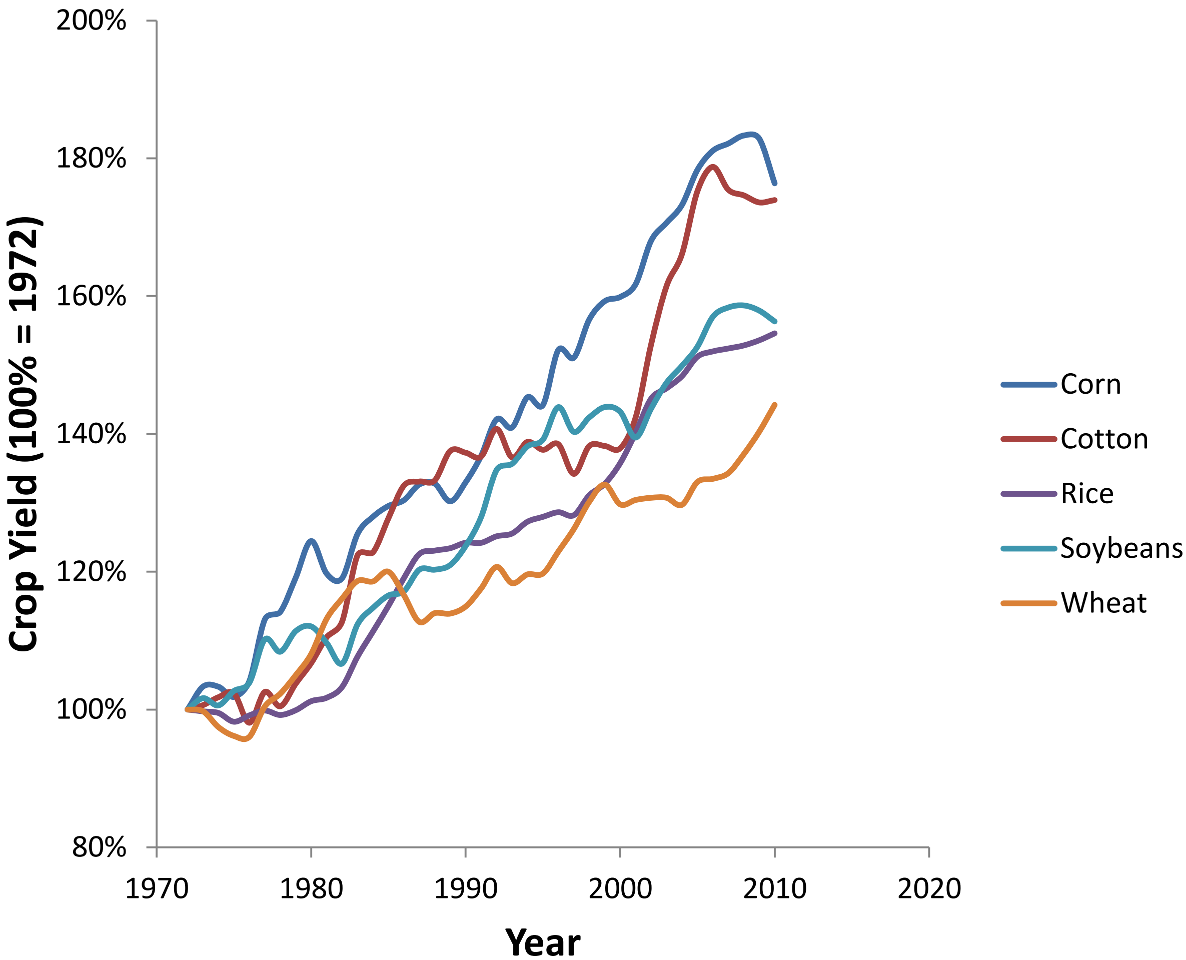

Figure 8. Crop yield trends from 1970 to 2012 using a five year running average with 100% equal to the average yield from 1970 to 1974 (USDA, 2013).

Conclusion

Despite challenges to the numerous methodologies for quantifying global water issues, there is consensus that water resources are inadequate in many areas of the world to meet present human needs, and that water limited areas will increase in the future. And while it will introduce uncertainty into the analysis, these metrics will need to be evaluated at regional scales to appropriately assess water scarcity, while at the same time not over-penalizing products that are derived solely from rainfall in these regions. A second point is that energy and water are tightly linked – while LCA approaches account for energy independently, the need for a dependable water supply for power generation should not be ignored when considering water risk. Finally, the data for products based on agricultural commodities is very time-sensitive and should be updated on a routine basis (5 year intervals suggested).

Understandably, industry sectors and business units need and want to understand and quantify water use throughout their supply chains. Sustainability initiatives offer a pre-competitive collaborative space for businesses to understand the issues and risks that natural resource scarcity could have on supply chain security. Businesses can act collectively to make large-scale changes in practices or business models that will have positive impacts on society, human health, and ecological systems. Likewise, large-scale changes by industry sectors could have the opposite effect if decisions are based on incomplete knowledge of the complexities and technical intricacies behind current models and metrics. This is especially true for decisions about products from agricultural systems which have typically been subject to the application of metrics developed for industrial systems – systems which are inadequate for capturing the complex plant, air, water and soil interactions and processes. There is clear need for irrigation water experts to engage with the various sustainability initiatives to lend their experience in addressing the complexities of agricultural water management.

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Evaluation of Soil Moisture Sensors

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Abstract. This study evaluated the measurement accuracy and repeatability of the EC-5 and 5TM soil volumetric water content (SVWC) sensors, MPS-2 and 200SS soil water potential (SWP) sensors, and 200TS soil temperature sensor. Six 183cm x 183cm x 71cm wooden compartments were built inside a greenhouse, and each compartment was filled with one type of soil from the Mississippi Delta. Sixty-six sensors with 18 data loggers were installed in the soil compartments to measure SVWC, SWP, and soil temperature. Soil samples were periodically collected from the compartments to determine SWVC using gravimetric method. SVWC measured by the sensor was compared with that determined by the gravimetric method. SVWC readings of the sensors have a linear correlation with the gravimetric SVWC (r^2=0.82). The correlation was used to calibrate the sensor readings. The SVWC and SWP sensors were capable of detecting general trend of soil moisture changes. However, their measurements varied significantly among the sensors and were influenced by soil property. To obtain accurate absolute soil moisture measurements, the sensors require soil-specific calibration. The 5TM, MPS-2, and 200TS sensors performed well in soil temperature measurement test. Individual temperature readings of those sensors were very close to the mean of all sensor readings.

Keywords. Soil moisture sensor, irrigation, soil water potential, soil water content, soil temperature

INTRODUCTION

Irrigation scheduling determines the time and amount of water to apply. Irrigation scheduling methods may be classified into three main categories: weather-based methods, soil moisture-based methods, and plant-based methods. Weather-based methods schedule irrigation based on the amount of water lost by plant evapotranspiration (ET) and the amount of effective rainfall and irrigation water entering into the plant root zone. Soil-based methods measure soil moisture levels in the plant root zone and apply water if there is water shortage for plants. Plant-based methods directly detect plant responses to water stress and initialize irrigation as plants indicate suffering from water stress.

Soil moisture sensors have been widely used to measure soil moisture status and determine supplementary water requirements by crops. Various types of sensing devices have been developed and made commercially available for water management applications in recent years. Evaluations have shown that each type of sensing device has its advantages and shortcomings in terms of accuracy, reliability, and cost (Basinger et al., 2003; Chanzy et al., 1998; Evett and Parkin, 2005; Seyfried and Murdock, 2004; Yao et al., 2004). The neutron probe has been shown to be a reliable tool for determining soil water content. However, its use of radioactive source requires special licensing and training for operation and has restricted its application in recent years. Meanwhile, electromagnetic (EM) sensors, such as electrical capacitance and resistance type sensors, and time-domain reflectometer (TDR) devices have been rapidly developed and widely adopted for soil water measurement (Dukes and Scholberg, 2004; Fares and Alva, 2000; Miranda et al., 2005; Seyfried and Murdock, 2001; Vellidis et al., 2008). Yoder et al. (1997) tested 23 soil water sensors representing eight sensor types, including neutron probe, electrical capacitance sensors, electrical resistance sensors, TDR devices, and heat dissipation sensors with carefully controlled soil water contents. Measurement errors of the volumetric water content of the soil were determined for each sensor. The results indicated that the capacitance sensors had the best performance in the study. Leib et al. (2003) evaluated soil moisture sensors of several different brands and types under identical operating conditions in the field for three years. They found that most sensors were able to follow the general trends of soil water or potential changes during the growing season, but that actual measured values varied significantly between sensors and calibrated neutron probe measurements. It was suggested that a soil specific calibration of each sensor was necessary to obtain high accuracy in the measurements. Evett et al. (2006) compared several EM sensors with a neutron moisture meter in measuring water content of three soils. It was found that all EM sensing devices under test were sensitive to soil temperature differences. Similar to the suggestion by Leib et al. (2003), the authors recommended that all of the EM sensing devices would require separate calibrations for different soil horizons. Previous research indicated that the EM sensors were inexpensive, easy to install and maintain, and able to provide reliable information for irrigation scheduling and control. However, the sensors must be well-calibrated under specific operation conditions including soil type and temperature.

Objectives of this study were to evaluate and calibrate soil moisture sensors (several not included in previously cited studies) with various types of Mississippi Delta soils.

MATERIALS AND METHODS

Sensor Installation

Six 183cm x 183cm x 71cm wood compartments were built in a greenhouse. Six different types of Mississippi Delta soils around Stoneville, Mississippi were collected, and one type of the soil was filled in each soil compartment (Figure 1). Water was applied using a sprinkler installed over the compartments to make the soils in the compartments saturated. This process was repeated four times to allow the soils to resettle in the compartments. Types of soil used were Bosket very fine sandy loam (BVFSL), Sharkey clay (SC), Dundee silty clay (DSC), Dundee very fine sandy loam (DVFSL), Dundee silty clay loam (DSCL), and Tunica clay (TC). Physical properties of the soils were analyzed at the soil test lab of Mississippi State University (Table 1). Sixty-six soil moisture and temperature sensors were tested for measuring soil volumetric water content (SVWC), soil water potential (SWP), and soil temperature, including:

- Eighteen EC-5 SVWC sensors,
- Six 5TM SVWC sensors,
- Eighteen MPS-2 SWP sensors,
- Eighteen 200SS SWP sensors, and

- Six 200TS temperature sensors.

The EC-5, 5TM, MPS-2 sensors were the products of Decagon Devices (Pullman, WA) while the 200SS and the 200TS sensors were manufactured by the Irrometer Company (Riverside, CA). The EC-5 sensors measure SVWC only. The 5TM sensor is able to measure SVWC and soil temperature. The 200SS sensor is only able to measure SWP while the MPS-2 can measure both SWP and soil temperature.

There were three EC-5, three MPS-2, one 5TM, three 200SS, and one 200TS sensors installed in each soil compartment. A hole with a size of 46cm in diameter and 38cm deep was made at the center of each soil compartment for sensor installation. The sensors were installed at a depth of 30.5cm along the perimeter of the hole with a center to center spacing of about 12.7cm between the sensors. The installation was performed according to the instruction given by each sensor's manufacturer. After all sensors were installed, the hole was refilled with the soil dug out and water was applied to make the soils saturated.

Data Collection

Twelve Decagon data loggers (EM50R, Decagon Devices, Pullman, WA) were used to collect data from the EC-5, MPS-2, and 5TM sensors. Six Watermark monitors (900M, Irrometer Company, Riverside, CA) were employed to record the data measured by the 200SS and 200TS sensors. Default calibration for "mineral" soil was selected for Decagon data loggers. A soil temperature sensor was connected to channel 1 of the Irrometer monitors for temperature compensation in its water potential measurement. Data logging devices were set to automatically collect data from the sensors at a time interval of one hour.

Five cycles of soil sample collection were conducted during the 3-month test. In each cycle, three soil samples with 2 replicates were randomly collected using a soil sampler in each soil compartment. Soil samples were taken at a depth of 27.3cm-33.7cm to represent the soil at the depth of 30.5cm in which soil moisture was measured. Sample size was 5.4cm in diameter and 3.0cm deep. After being collected from the soil compartment, the samples were immediately weighed using a balance for wet weight, and then were dried by oven at 110 ^oC until completely dry. Dried samples were weighted for dry mass weight.

Volumetric water content of the soil sample, θ, was determined using the formula below.

$$\theta = \frac{V_l}{V_t} = \frac{(W_w - W_d)}{V_t\,\rho_w} \qquad (1)$$

where V_l is the volume of the water, V_t is the total volume of the sample, W_w is the wet weight of the sample, W_d is the dry weight of the sample, and ρ_w is the water density.

Data Analysis

Soil moisture, soil water potential, and soil temperature of the six soil types were continuously monitored and recorded for three months. All data were downloaded from the data logging devices and processed for calibration and evaluation of the sensors. The volumetric water contents determined using the oven-dried method as described above were compared with those measured by Decagon's EC-5 and 5TM sensors. Correlation between the readings of the EC-5 and 5TM sensors and the oven-dried SVWC was established and used to calibrate those sensor measurements. An ANOVA was performed with SAS software (SAS Institute Inc., Cary, NC) to evaluate the differences in soil moisture and soil temperature measurements by sensor and soil type.

RESULTS AND DISCUSSION

Soil Volumetric Water Content

The SVWC readings measured by the EC-5 and 5TM sensors have a linear correlation with the oven-dried SVWC (r^2=0.82) (Figure 2). It was obvious that the sensors over-estimated the SVWC using the Decagon "mineral soil" calibration. The correlation between the oven-dried SVWC and the sensor readings, $y=0.6508x+1.7612$, was then used to calibrate the sensor readings. Figure 3 showed a comparison of oven-dried SVWC with the calibrated sensor-measured SVWC in five soil sampling cycles. Average SVWC and the sensor's prediction error across sampling cycles were given in Table 2. Sensors' prediction error, defined as predicted minus observed percent volumetric water content, varied from -8.6% to 11.8% depending on the soil type. The minimum prediction error was 2.7% with DSC soil while the maximum was 11.8% with the DSCL.

In general, sensor-measured SVWC followed the trend of soil moisture changes for all types of soils during the 3-month test. But the SVWC determined by individual sensors varied. The means of SVWC measured by each EC-5 and 5TM sensors were given in Table 3. ANOVA analysis revealed that the SVWC measured by the EC-5 #2 and #3 sensor in soils BVFSL and TC were not significantly different. However, the rest of the measurements by each EC-5 sensor within the same soil type varied significantly. The SVWC determined by the 5TM sensor was significantly different from that by the EC-5 sensors in all types of soils. Performance consistency across the sensors should be taken into consideration in applications of these sensors.

Soil Water Potential

Figure 4 compared SWP measured by the MPS-2 and 200SS sensors in the five soil sampling cycles. In BVFSL and DVFSL soils, the measurements by these two types of sensors followed each other fairly well. SWP values by the MPS-2 sensors were much higher than those of the 200SS for DSC and DSCL soils. However, in SC and TC soils, the SWP values measured by the 200SS showed a trend of being greater than those of the MPS-2 sensors. This result indicates soil type has an effect on the performance of the sensors.

Both the MPS-2 and 200SS sensors showed their capability in detecting the tendency of SWP changes. However, similar to the SVWC sensors, under the same test conditions the outputs of same model sensors could vary significantly (Table 4, Table 5). For example, as given in Table 4, the SWP measured by the MPS-2 #1 sensor in BVFSL soil was consistent with that of the MPS-2 #3, but significantly different from that of the MPS-2 #2 sensor. Taking another example in Table 5, the SWP measurements by the 200SS #2 and #3 sensors in BVFSL soil agreed with each other well, but they were significantly different from the measurement by the 200SS #1. Table 6 provides a comparison between the mean of SWP measurements by all MPS-2 sensors and that by all 200SS sensors. It indicates that SWP measured by the MPS-2 sensors was significantly different from that by the 200SS sensors across all type of soils used in this study. The relative difference with DVFSL soil is the smallest while that with the DSCL was the biggest.

Soil Temperature

All soil temperature sensors performed very well with all types of soils in the test with individual temperature readings from each sensor very close to the mean of all sensor readings. Means of soil temperature measured by soil temperature sensors during the 3-month test are given in Table

7. ANOVA analysis indicates that soil temperatures determined by the sensors in each soil are not significantly different except two observations. One observation was related with the 5TM sensor in SC soil, in which the temperature measured by the 5TM was slightly higher than that by the other sensors. The other one involved the MPS-2 #1 sensor in TC soil, where this sensor's measurement was about 2.5% lower than the other sensors (Table 7). Soil temperature varied during the testing period and the measurements from all sensors followed the same trend and agreed well (Figure 5). Average soil temperature in different type of soils was about the same in this case.

CONCLUSIONS

The EC-5 and 5TM SVWC sensors, the MPS-2 and 200SS SWP sensors, and the 200TS soil temperature sensors were evaluated with six Mississippi Delta soils. Volumetric water contents of the soils were determined using the oven-drying method. Oven-dried volumetric water contents were compared with the sensor measurements to find their correlation, and their relationship was used to calibrate the SVWC sensor measurements. Results indicated readings from the EC-5 and 5TM sensors had a linear relationship with oven-dried SVWC (r^2=0.82). In general, the soil moisture sensors were capable of detecting the trend of soil moisture changes. However, the accuracy of sensor measurements varied significantly between different sensor models and among the sensors within the same model. To obtain accurate absolute measurements, the soil moisture sensors should be calibrated with specific soils. Soil temperature measurement could be consistently obtained using the 5TM, MPS-2, and 200TS sensors.

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Figure 1. Six soil compartments with the sensors and data loggers installed.

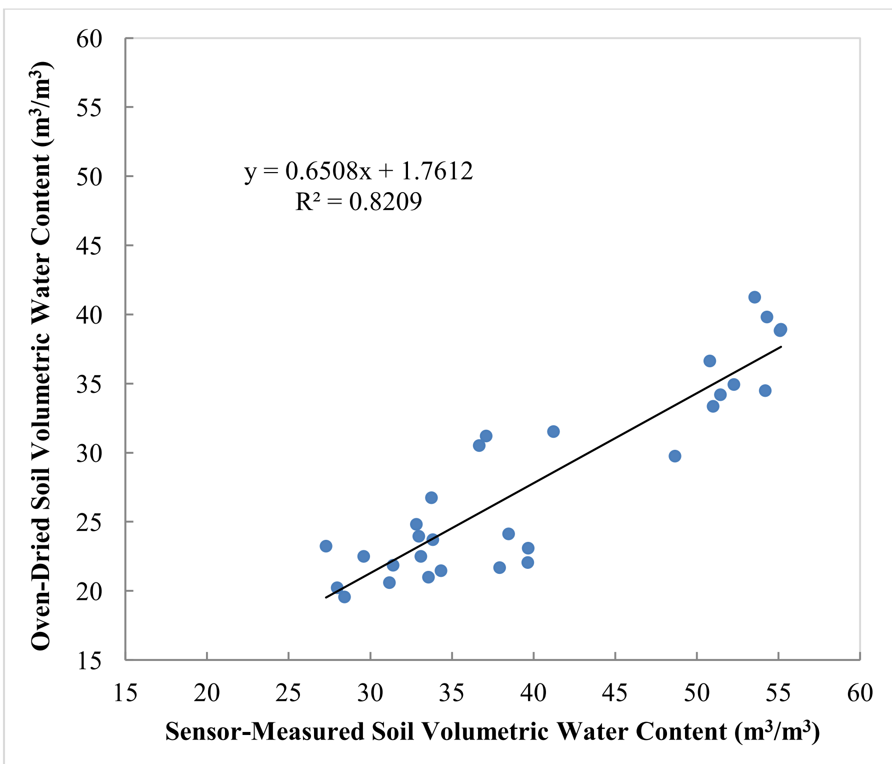

Figure 2. Relationship between sensor-measured SVWC and the oven-dried SVWC.

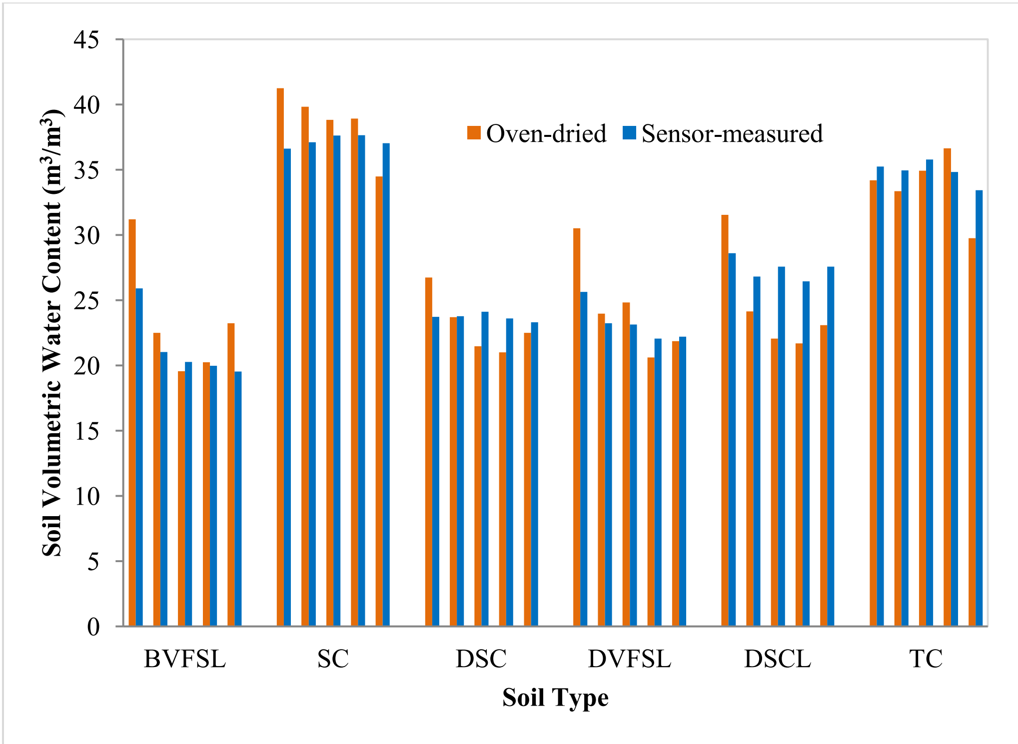

Figure 3. Comparison of calibrated sensor-measured SVWC with the oven-dried SVWC.

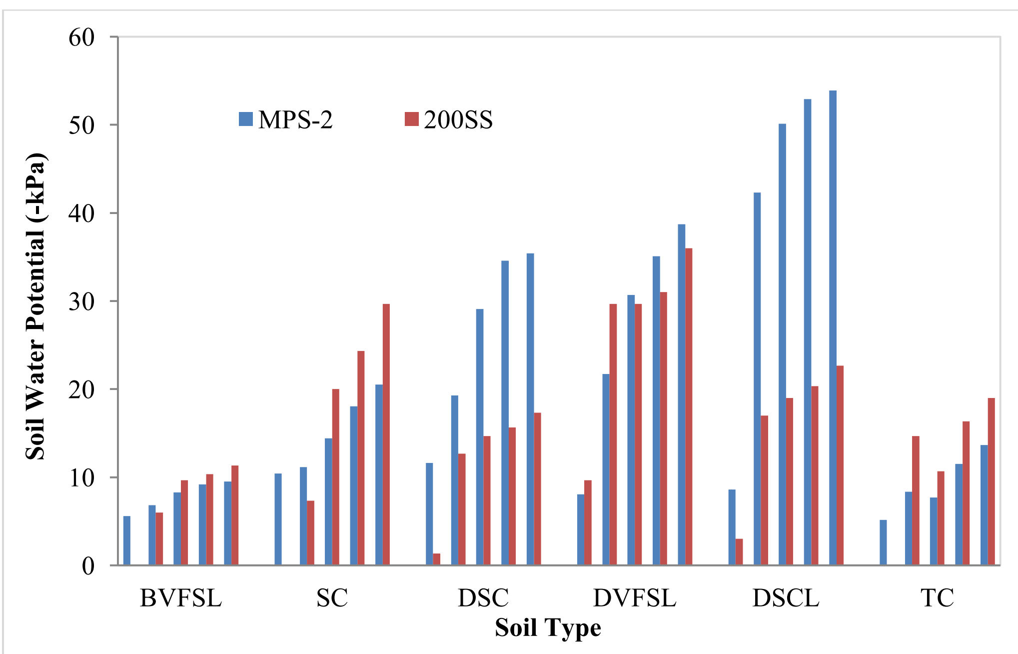

Figure 4. Soil water potential measured by the MPS-2 and 200SS sensors in different soils.

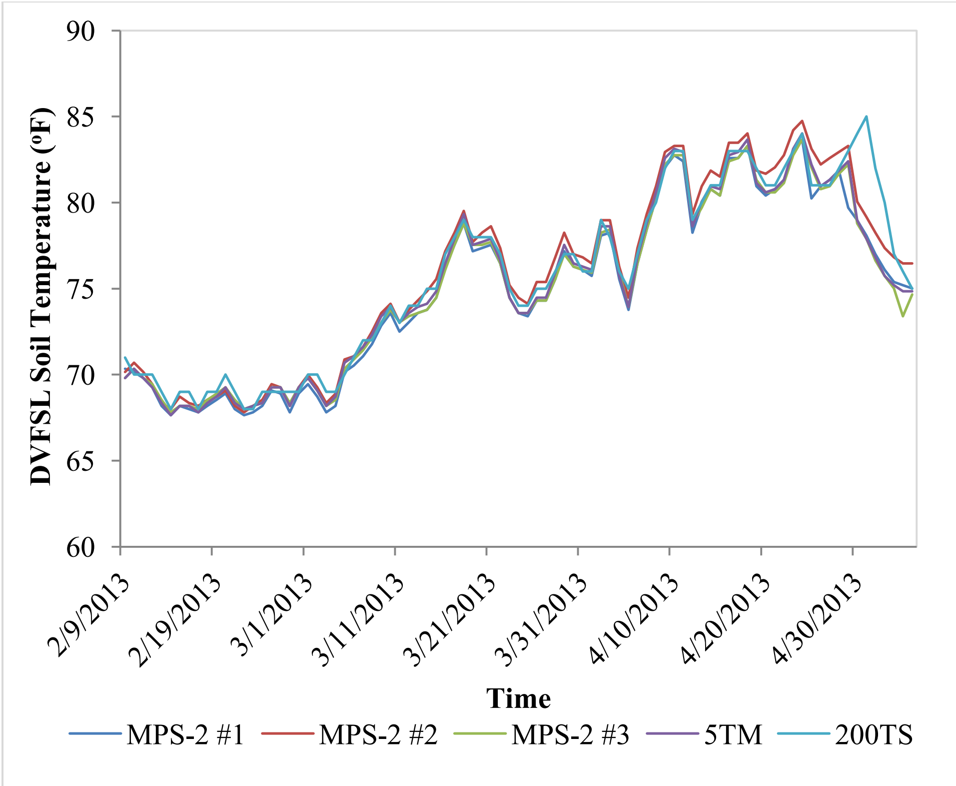

Figure 5. DVFSL soil temperature determined using different sensors.

Table 1. Physical properties of soils used in the sensor test

	Clay (%)	Silt (%)	Sand (%)	Texture
BVFSL	2.5	42	55.5	Sandy Loam
SC	23.75	67.75	8.5	Silt Loam
DSC	8.75	54.5	36.75	Silt Loam
DVFSL	8.75	67.5	23.75	Silt Loam
DSCL	10	72.5	17.5	Silt Loam
TC	21.25	69.5	9.25	Silt Loam

Table 2. Average of soil volumetric water content and sensor measurement error in different soils.

	BVFSL	SC	DSC	DVFSL	DSCL	TC
Oven-dried (m^3/m^3)	23.35	38.67	23.08	24.35	24.5	33.78
Sensor-measured (m^3/m^3)	21.34	37.20	23.70	23.24	27.40	34.85
Error (%)	-8.6	-3.8	2.7	-4.5	11.8	3.2

Table 3. Means of soil volumetric content measured by the EC-5 and 5TM sensors during the 3-month test. The means with same letter under each soil type are not significantly different at the 0.05 level.

	BVFSL	SC	DSC	DVFSL	DSCL	TC
EC-5 #1 (m^3/m^3)	18.0[c]	36.5[c]	16.7[c]	19.5[d]	25.3[c]	33.7[b]
EC-5 #2 (m^3/m^3)	24.5[a]	37.2[b]	26.4[b]	27.8[a]	27.9[b]	36.1[a]
EC-5 #3 (m^3/m^3)	24.2[a]	39.5[a]	29.6[a]	25.5[b]	32.2[a]	37.6[a]
5TM (m^3/m^3)	20.0[b]	35.3[d]	NA*	21.7[c]	24.8[d]	29.1[c]

*The sensor failed during the test.

Table 4. Means of soil water potential measured by the MPS-2 sensors during the 3-month test. Means with same letter under each soil type are not significantly different at the 0.05 level.

	BVFSL	SC	DSC	DVFSL	DSCL	TC
MPS-2 #1 (-kPa)	7.4[b]	13.0[b]	16.9[a]	17.1[a]	34.0[b]	10.7[b]
MPS-2 #2 (-kPa)	6.3[a]	12.3[a,b]	19.2[a]	17.2[a]	48.6[c]	6.5[a]
MPS-2 #3 (-kPa)	7.4[b]	11.9[a]	24.9[b]	29.6[b]	28.9[a]	5.7[a]

Table 5. Means of soil water potential measured by the 200SS sensors during the 3-month test. Means with same letter under each soil type are not significantly different at the 0.05 level.

	BVFSL	SC	DSC	DVFSL	DSCL	TC
200SS #1 (-kPa)	3.2^{b}	23.1^{a}	8.6^{c}	26.9^{a}	12.1^{c}	8.9^{b}
200SS #2 (-kPa)	6.4^{a}	4.8^{b}	10.8^{b}	22.8^{b}	15.2^{b}	7.7^{b}
200SS #3 (-kPa)	6.1^{a}	4.4^{b}	13.9^{a}	26.2^{a}	17.8^{a}	12.9^{a}

Table 6. Means of average soil water potential measured by the MPS-2 and 200SS sensors during the 3-month test. Means with same letter under each soil type are not significantly different at the 0.05 level.

	BVFSL	SC	DSC	DVFSL	DSCL	TC
MPS-2 Avg. (-kPa)	7.0^{b}	12.4^{a}	20.3^{b}	21.2^{a}	37.2^{b}	7.6^{a}
200SS Avg. (-kPa)	5.3^{a}	10.6^{a}	11.1^{a}	25.0^{b}	14.7^{a}	9.8^{b}

Table 7. Means of soil temperature measured by soil temperature sensors during the 3-month test. Means with same letter under each soil type are not significantly different at the 0.05 level.

	BVFSL	SC	DSC	DVFSL	DSCL	TC
MPS-2 #1 (^{o}F)	75.5^{a}	75.7^{b}	76.5^{a}	76.5^{a}	76.4^{a}	75.9^{b}
MPS-2 #2 (^{o}F)	75.4^{a}	75.9^{b}	76.5^{a}	76.5^{a}	76.1^{a}	78.3^{a}
MPS-2 #3 (^{o}F)	76.0^{a}	75.7^{b}	76.3^{a}	76.3^{a}	77.1^{a}	$77.3^{a,b}$
5TM (^{o}F)	76.0^{a}	77.6^{a}	77.1^{a}	77.1^{a}	77.0^{a}	$78.1^{a,b}$
200TS (^{o}F)	76.0^{a}	75.6^{b}	75.8^{a}	75.8^{a}	76.0^{a}	78.1^{a}

Seasonal near-continuous patterns of leaf-to-air vapor pressure deficits in differentially irrigated cotton: potential importance in assessing water demand.

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Abstract

The application of water to crops, in the needed amount, at the right moment in time, is important. The water status of the crop is often used to determine the need for irrigation. Since the water status of a crop can be difficult to measure directly it is often inferred from the environment. Measurement of the above ground environment can be automated and the data can used used in models to predict irrigation amount and timing. The vapor pressure deficit (VPD) of the air is a good indicator of the potential water need. VPD is calculated with the assumption that the temperature of the canopy is similar to air temperature. Canopy temperature of cotton was monitored across irrigation regimes and was used to calculate leaf-to-airVPD. Leaf-to-airVPD declined with increasing irrigation amounts. The value of leaf-to-airVPD in the prediction of potential ET for the crops was assessed.

Keywords

canopy temperature, water defcits, cotton, vapor pressure deficit VPD

Introduction.

The application of water to crops, in the appropriate amount, at the right moment in time, is the underlying principle of irrigation management. These decisions, correctly made, several times over a growing season, result in successful production of crop. Errors in irrigation can result in either unintended crop water stresses or inefficient use of water associated with under or over irrigation respectively. With agricultural water generally increasing in price and/or declining in availability, improvements in irrigation management are increasingly important.

The soil, as the source of water for transpiration, is generally viewed as a reservoir that serves to buffer the water use by the plant. Between a saturated condition and the point at which water can no longer be withdrawn by the plant, the uptake of water by roots is a continuously variable process that involves both physical and biological constraints.

Irrigation management is often achieved through an iterative process of adding water to the soil, assessing the amount water used by the plant between irrigation events, and applying an amount of water sufficient to meet the needs of the plant until the next irrigation event. The physics of soil water are well understood, though often difficult to characterize in practice. The use of water by the plant is less well defined and generally difficult to characterize.

The water status of the plant is often described in terms of a balance between soil water available to the plant and the amount needed by the plant. Evaporation of water from the interior of the leaf to the atmosphere (transpiration) accounts for the overwhelming fraction of the water required by the plant over its lifespan. This process of water movement from the soil to the atmosphere serves several purposes; uptake and transport of nutrients from the soil, hydration of cells and dissipation of potentially harmful radiant energy. The water status of the crop is often used to determine the need for irrigation. Since the water status of a crop can be difficult to measure directly it is often inferred from the environment. Since the measurement of the above ground environment can be automated, such data is used in models to predict irrigation amount and timing.

The driving force for movement of water through the plant from the roots to the atmosphere is the evaporation of water at the leaf-to-air interface that results in the net movement of water from the plant to the atmosphere i.e water use. In order for water to evaporate from the leaf-to-air interface there are 2 conditions that must be met; 1) there must energy sufficient to convert the water from liquid to vapor and 2) a gradient in water vapor across the leaf-to-air boundary. The sun provides radiant energy sufficient to accomplish the vaporization and the inherent dryness of the atmosphere results in the needed gradient.

Given that the air inside the leaf is normally saturated with water vapor and that the atmosphere is seldom, if ever, saturated there is generally a water vapor gradient sufficient for evaporation. The magnitude of the gradient for leaf-to-air movement of water vapor is generally expressed in terms of the vapor pressure deficit of the atmosphere that is commonly abbreviated as VPD. The VPD of atmospheric water vapor, at any moment of time, is calculated as the difference between the vapor pressure of the air at saturation and the measured vapor pressure of the air. The saturation vapor pressure is a chemical parameter that is primarily a function of temperature and atmospheric pressure, both relatively simple to measure. The actual vapor pressure is a function of temperature and measured humidity. It can be derived from measured dewpoint temperature, wet bulb temperature measured with a psychrometer, or most commonly from relative humidity and air temperature.

The vapor pressure deficit (VPD) of the air (airVPD) is a measured environmental parameter that is generally used as an indicator of the evaporative "demand" of the atmosphere for water. Given sufficient available soil moisture, it is expected that the evaporative demand is an indicator of water use and, as such, provides information on transpirational water use by the plant. The temperature of the air at the time of measurement is used to calculate both the saturation vapor pressure of the air and the actual vapor pressure of the air. The saturation vapor pressure, when based on air temperature, does not explicitly define the gradient between the interior of the leaf and the air when the temperature of the air is not equal to the temperature of the leaf. In an effort to quantify the extent of this possible difference, a measure of the plant temperature is needed. Canopy temperature measurements provide a means to accomplish this.

In this study we have used a dataset consisting of near-continuous canopy temperature in cotton over a 65-day period to investigate the potential value of leaf-to-air canopy temperatures in the quantification of water use by cotton. Recent advances have made the continuous measurement of canopy temperature in the field somewhat simpler we believe there may be some value in the use of leaf-to-air VPD in the assessment of plant/environment interactions.

Materials and Methods

Cotton (Fibermax 9180) was planted on May 14th, 2009 and was grown under 4 irrigation regimes which applied 0mm, 1.5mm, 3.0mm or 6mm of irrigation on a daily basis using a sub-surface drip irrigation system. Cultural practices were typical for the region.

Canopy temperature measurement

Canopy temperature of cotton was monitored across irrigation regimes using a Smartcrop IRT system. Canopy temperature was measured on 1-minute intervals and reported as 15-minute averages over a 65-day period in 2009 in Lubbock TX. Temperature was collected from a single IIRT sensor in each plot.

VPD calculations

Relative humidity and air temperature were monitored on a 1-minute interval with 15-minute averages reported at 2 meters above ground level at the edge of the field. Air VPD was calculated on a 15-minute interval based on measured air temperature and relative humidity over the 65-day interval by equation 1.

1) Air VPD= VP air saturation - VP air actual saturation

Leaf-to-air VPD

The leaf-to-air VPD was calculated in a manner similar to the airVPD calculation, with the substitution of canopy temperature for air temperature in the calculation of the saturating vapor pressure by equation 2.

2) Leaf-to-air VPD= VP canopy saturation - VP air actual saturation

Results

Air and canopy temperatures

The seasonal air and canopy temperature for the 4 cotton irrigation regimes in 2009 are shown in Figure1. The effect of variable plant water status, generated by the irrigation regimes, is present though not readily apparent.

In figure 2 air and canopy temperature data are shown in the context of time surfaces that present the temperatures over time with DOY as the X axis, time of day (midnight to midnight) on the Z axis and the temperature as the Y axis. A side view and a nadir view are shown. These figures indicate that the irrigation regimes resulted in differences in air and canopy temperature in terms of their magnitude and temporal distribution over the season.

Figure 3 shows the values of air VPD and leaf-to-air VPD in a time surface format. The upper panel indicates the seasonal pattern and magnitude of the air VPD which is the same for all irrigation regimes. The lower panels indicate the effect of irrigation-related differences in canopy temperature on the leaf-to-air VPD. Irrigation-related differences are evident in terms of both magnitude and seasonal distribution of leaf-to-air VPD. At higher irrigation levels (6mm and 3mm), the canopy temperatures are generally lower than air temperatures resulting in leaf-to-air VPD values that are lower that the air VPD while in the lower irrigation levels (1.5mm and 0mm), the canopy temperatures are higher than air temperatures resulting in leaf-to-air VPD values that are higher than air VPD.

Figure 4 shows the distribution of leaf-to-air VPD as functions of the air temperature. The overall pattern indicates that in the 6mm irrigation treatment the maximum leaf-to-air VPD values are constrained to less than 2kPA with the lowest irrigation regime experiencing leaf-to-air VPD values up to 7kPa. Leaf-to-air VPD values for the middle irrigation amounts produce leaf-to-air VPD vales that are intermediate between the extremes.

Discussion

It is evident that irrigation-related differences in the magnitude and seasonal distribution of canopy temperatures result in large variation in leaf-to-air VPD across irrigation levels in cotton. It is perhaps worth noting that seasonal analyses of leaf-to-air VPD have been made simpler through recent advances in the technology available for canopy temperature monitoring. There is a great deal of literature that describes plant water use in terms of air VPD alone. Such approaches have proven valuable in understanding plant/environment interactions and have been widely applied in irrigation management. While the value of air VPD in such analyses is unmistakable, it is possible that the inclusion of leaf-to-air VPD measurements may serve to refine our understandings.

Given the proven utility of air VPD measurements in understanding plant/environment interactions, it is reasonable question the wisdom of adding another variable to consider. What is clear is that the leaf-to-air VPD as measured is an improved estimate of the gradient for water movement from the leaf to the atmosphere, when the temperature of the leaf is not equal to that of the surrounding air. In light of the probability that reduced irrigation and increased water deficits will become more commonplace in agriculture, the inclusion of leaf-to-air VPD in physiological and irrigation studies may prove to be useful.

While these leaf-to-air VPD values differ from the air VPD values measured purely in terms of the environment, the utility, if any, of leaf-to-air VPD is open to debate. The extent to which leaf-to-air VPD might provide additional insight into the interactions between plants and their environments and the effect of irrigation management on these interactions will be the object of additional studies.

Figure 1. Air and canopy temperature collected in cotton over 4 irrigation regimes for 65 days in 2009.

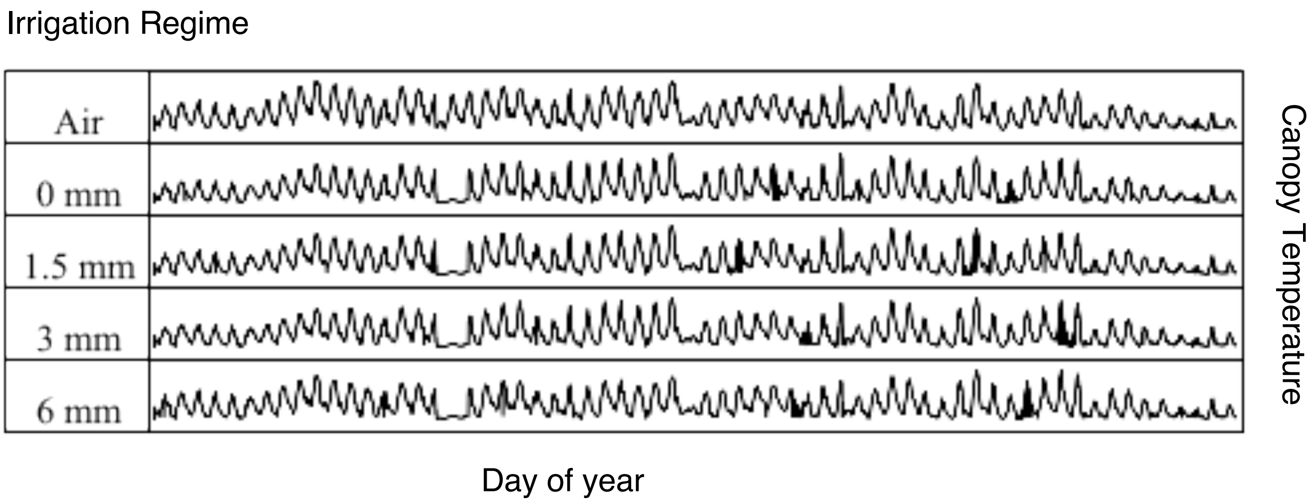


Figure 2. Time surfaces of air and canopy temperature collected in cotton over 4 irrigation regimes for 65 days in 2009. The time surfaces show the day of year, time of day, and temperature as the elevation. Green color indicates temperature of 28°C, blue indicates temperatures <28°C and yellow and red indicate temperatures >28°C.

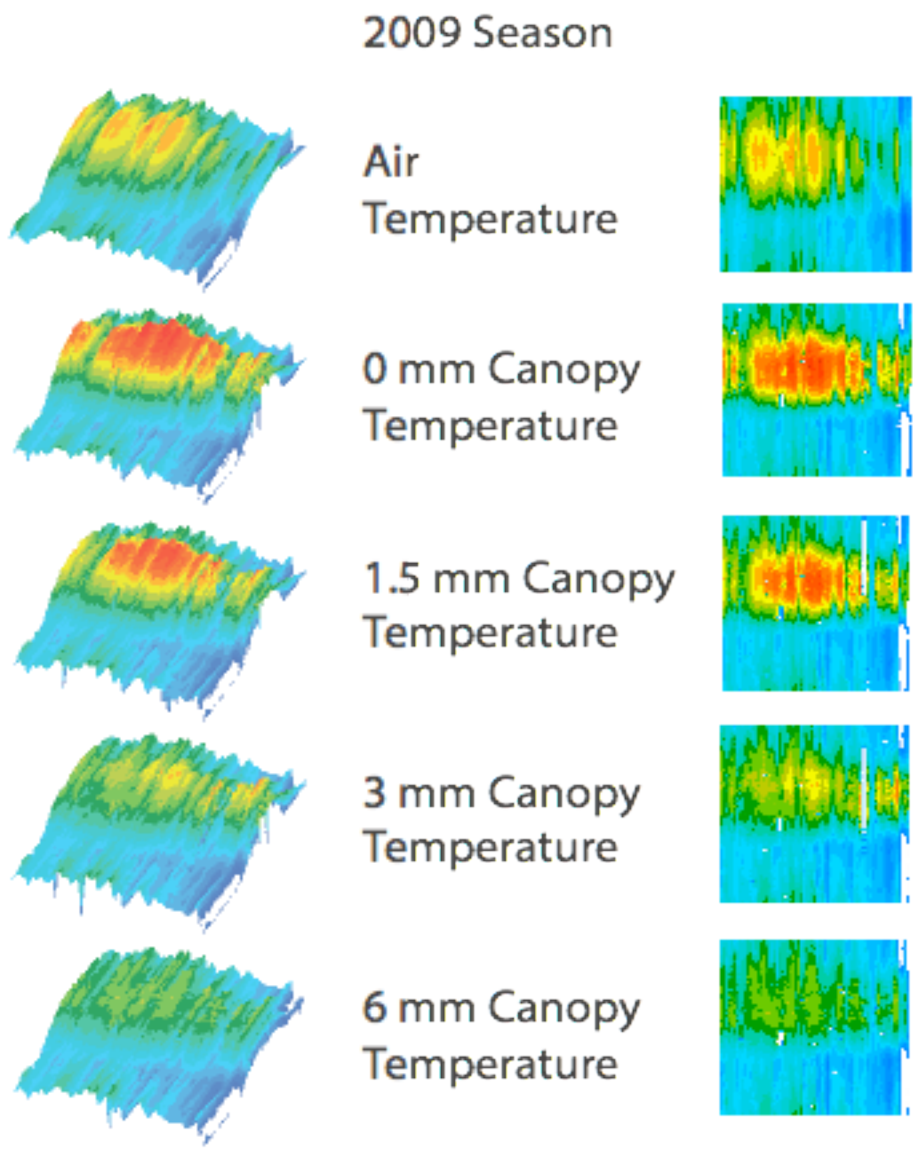


Figure 3. Time surfaces of air VPD and leaf-to-air VPD measured in cotton over 4 irrigation regimes for 65 days in 2009. The time surfaces show the day of year, time of day, and air VPD (AT-VPD) and leaf-to-air VPD (CTVPD) as the elevation. Dark green color indicates VPD values of 0, yellow indicates values ~3, and red indicates values >4.

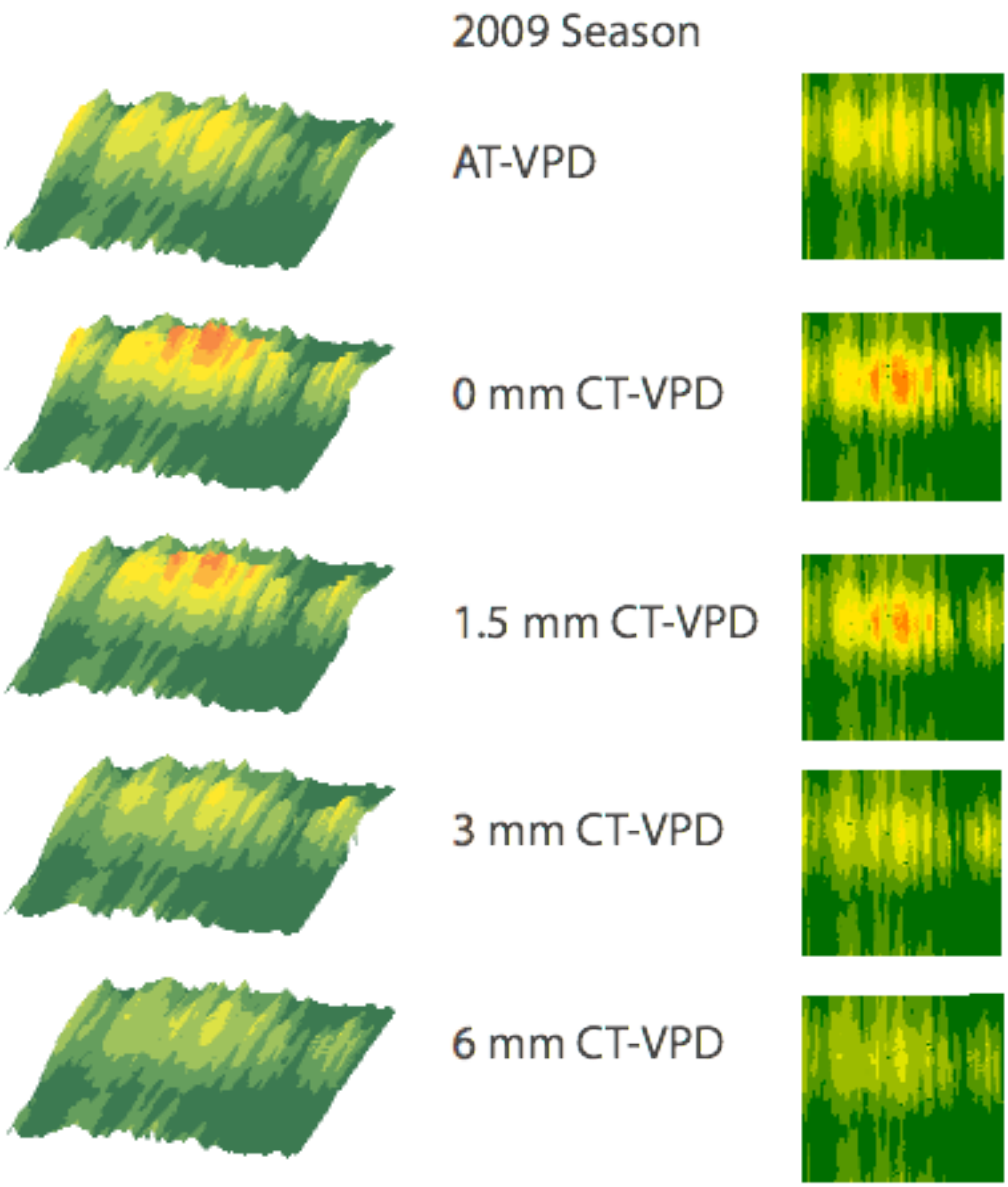
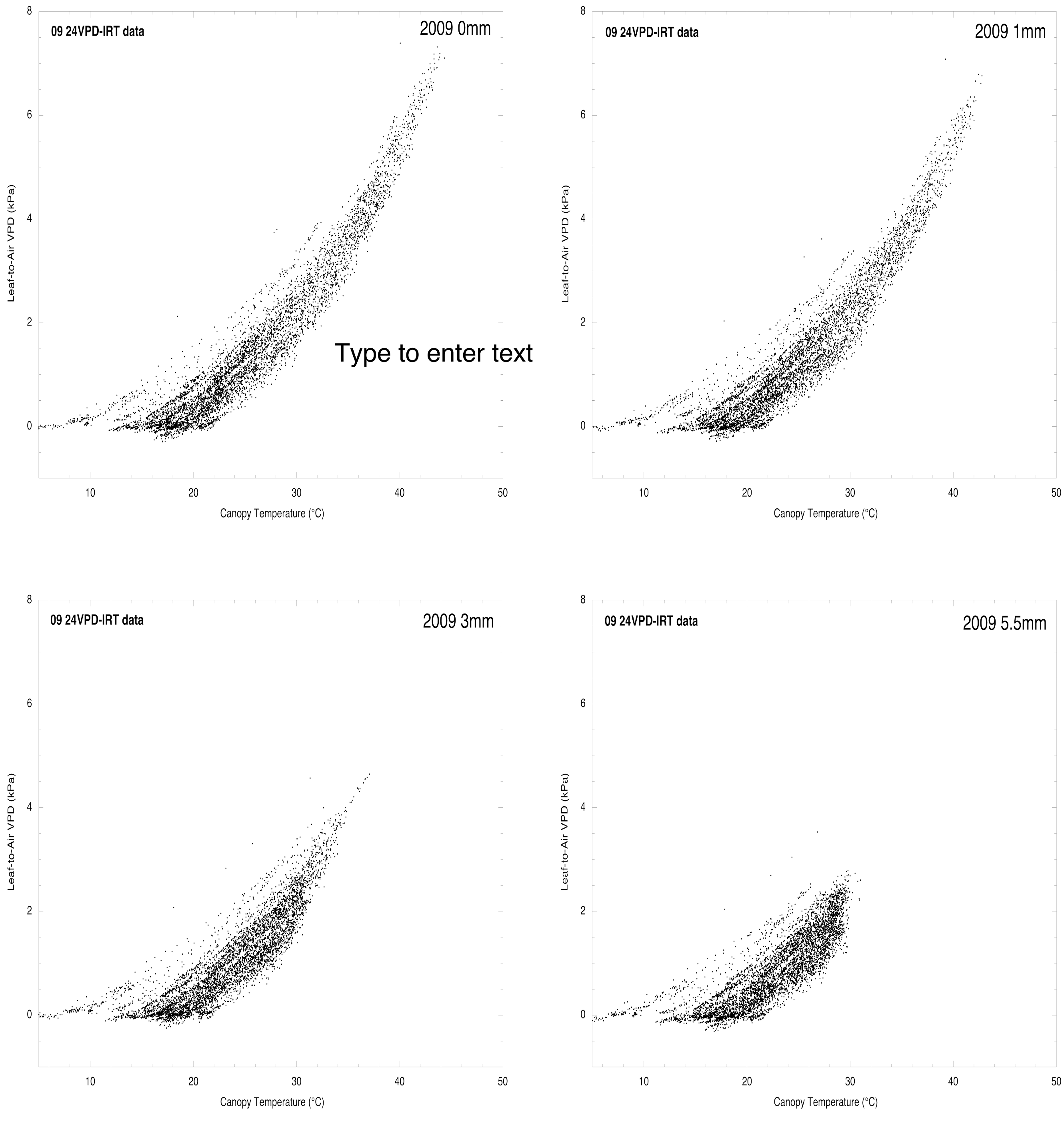


Figure 4. Leaf-to-air VPD. Leaf-to-air VPD as a function of canopy temperature in cotton under 4 irrigation regimes.



Data Standards for Precision Irrigation

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Abstract. *Technology has provided many tools to help growers irrigate their land more efficiently. However, these tools rarely work together well, and; growers using them must invest extra effort to bring the information together. Improving interoperability among these tools will reduce users' effort, increase adoption, and lead to greater water use efficiency through improved accuracy and precision of irrigation management.*

Over the past year, a group of companies began collaborating to develop data standards to enable interoperability of environmental sensors, soil mapping, advanced pump controls, variable rate irrigation, and software applications. The goal is an industry-wide format that will enable the exchange of data currently stored in a variety of proprietary formats, and use of the data by irrigation management systems. This work is currently taking place in the context of AgGateway's Water Management Group and PAIL project. We will present the results of this collaboration and invite future participation.

Keywords. Irrigation, Data Standards, Decision Support Systems, Schema, Use Case, System Integration

Introduction

Irrigated agriculture in the US accounts for 80-90% of the consumptive water use and approximately 40% of the value of value of agricultural production(USDA, 2009; Schaible and Aillery, 2012). This value, totaling nearly $118 billion, is produced on 57 million acres. Given the increasing challenges in water availability caused by climate change, and the likelihood of increased water conflicts from competing users, irrigated agriculture must increase its efficiency without sacrificing a reduction in the value it produces (Schaible and Aillery, 2012). Much of this efficiency can be derived through application of precision irrigation technologies, and on-farm management systems that facilitate sound agricultural practices. However, less than 10% of irrigated farms use any type of advanced decision support tools or technologies (USDA, 2009). Improving adoption of these technologies is critical to increasing efficiency.

There are a variety of technologies available for precision management of irrigation. Remotely actuated center pivots, drip irrigation systems, soil moisture sensing, on-farm weather stations all enable precise application with precise timing. Numerous software tools exist for deciding when and how much water to apply. However, rarely do these tools interoperate effectively. Data must be moved manually from one application to another and the burden is on the grower to do the data management.

IN 2011 the Northwest Energy Efficiency Alliance (NEEA) convened a group of irrigation expert to discuss issues that will lead to improved energy efficiency of agricultural irrigation. One of the conclusions from that conference was that the irrigation industry needs to support more integration of agricultural technologies. To that end, a group of companies, industry representatives, academics, and interested parties are collaborating to address the integration problem. This project, called Precision Ag Irrigation Leadership (PAIL), has the specific goal of producing a set of data exchange standards[1] that will enable development of more efficient and easier to use solutions for irrigation management.

An Integrated Solution

Part of the motivation for the PAIL project is the need for an integrated irrigation management system. A great variety of technologies exist for precision irrigation (Smith et al., 2010) and many of these technologies have been available for many years. The nature of irrigation management is such that using all these technologies places and additional burden on the decision maker. The source of this burden is the lack of integration. Nearly all of the information must be moved by the operator.

To provide a conceptual foundation for the data standards development, a fully integrated decision support system in proposed. This system, shown conceptually in Figure 1, will take data from as many sources as is practical, integrate the information using a decision support system, and deliver the irrigation recommendations to the appropriate irrigation system components. The integrated system is a goal as well as a foundation. Today, building a system as shown in Figure 1 would be a significant undertaking. The work and technical expertise required would put this system out of reach of all but the most sophisticated farms. When the data standards have been developed and adopted, constructing such a system would be practical and perhaps even common.

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[1] In this document the terms 'data standard' and API (application programming interface) are used interchangeably.

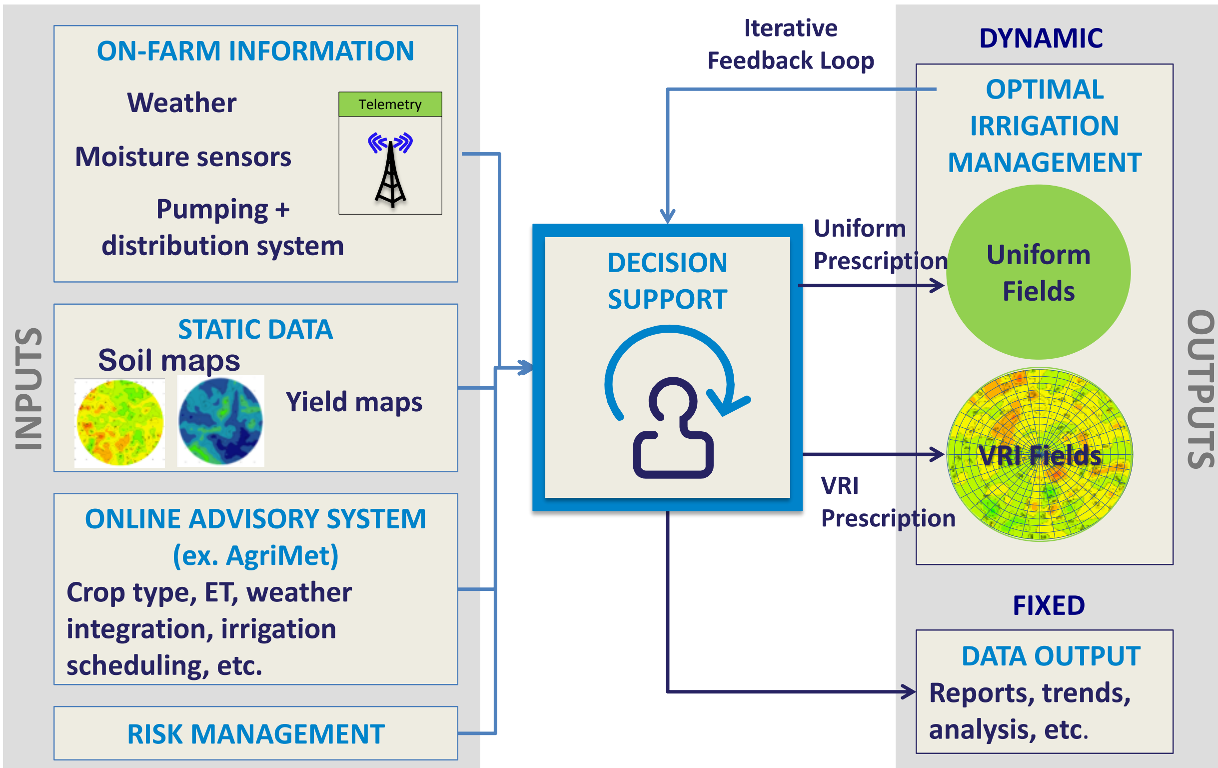

Figure 1 Representation of a fully integrated precision irrigation management system

To give a practical view of how growers will benefit from the API consider the following example. Suppose a grower has 15 quarter mile pivots. This grower is the quintessential modern agriculturalist. The grower uses efficient pivot irrigation systems, remote monitoring and control of the pivots and pumping systems, on-farm weather stations, soil moisture monitoring via remote telemetry, and software to use all these devices. Today, for this grower to implement scientific irrigation scheduling (SIS) he/she must keep records of how much water is applied and when, how much ET has occurred, and any precipitation that occurs. Soil moisture measurements must also be recorded and converted into volumetric water content. To schedule irrigations, the grower must integrate all of this information into a software tool that will calculate a water balance and estimate irrigation dates and amounts. Each of these sources of information is stored in or derived from a separate system. To use the scheduling system, the grower must spend a few minutes entering irrigation amounts, copy-pasting weather data, and evaluating results. This process may only take a few minutes per field but, with 15 fields, that time adds up. If the grower can do each field in 4 minutes then he/she can complete this process in about an hour. In water short or resource constrained conditions irrigation management occurs every day. This means the grower must spend an hour every day moving data around.

When the API is fully adopted a different scenario is possible. The system that monitors and controls the pivots will output irrigation history in a specific file format. Similarly, the weather station, soil moisture monitoring devices, and pumping controls will also use standard formats. The SIS software that calculates the water balance will read these standardized data files automatically. The SIS software can also output irrigation recommendations in a standard format; the same standard format that the pivot control system can read. With all of this integration in place the grower only needs to review, modify, or approve the schedules generated by the system. In this scenario the technologies in use are the same as those from the previous scenario. But now, because of the integration the grower spends less time moving data around and more time benefiting from the technology.

The previous example makes the benefits to the grower apparent but there are also important benefits to the irrigation industry. Barriers to grower's adoption of new technology includes both the time/effort required to use the technology and the cost of acquiring it. Use of the API by industry will address both of these issues. The scenario described previously shows how the time/effort will be reduced. If we assume that growers have different levels of effort that prevents them from adopting and that this level varies between individuals, then by reducing the effort required there will be more potential adopters. Thus, adoption of the API increases the size of the market for advanced irrigation technologies

The API can address the cost issue also. The following example describes an integration effort that actually occurred between two companies in 2008. A significant amount of time and effort was invested by both companies. The collaboration was successful and both companies benefited from the project however, the costs were not trivial. If an API had been available both companies could have achieved the same goal with lest time investment required. This is how the API reduces costs for the grower: by reducing cost of development of new interoperability between existing systems, those savings can be passed on to the customer.

Summary: In 2009, CropMetrics and AgSense worked jointly to develop the industry's first wireless Variable Rate Irrigation solution.

Issue/Problem: CropMetrics developed a VRI speed control prescription program but did not have any way to implement or load the prescription file effectively on the center pivot. At the same time, all center pivots were limited on the number of application adjustments they could make.

Solution: Working collectively with AgSense, they developed a prescription data format to upload wirelessly to AgSense's pivot monitoring and control website via a new API protocol developed by AgSense. AgSense then controls the speed of the pivot to adjust water application based on the CropMetrics variable rate prescription file. This was the first full integration of variable rate speed control irrigation.

Collaboration: Without the close working collaboration of both companies, the success of this technology would have been delayed or halted. Working together to develop a data standard, made wireless data transfer possible with greatly improves the efficiency, effectiveness and overall simplicity of the technology today.

Business Success: The development of this VRI technology introduced new development by pivot manufacturers to improve hardware to accept similar capabilities as well as introduced business opportunity for agronomic service providers. Most importantly, this joint effort delivers a solution to improve water use efficiency and conserve our most valuable natural resource.

Target Market for an Integrated Ag Irrigation Solution

The USDA Economic Research Service (ERS) categorizes farms primarily on the basis of Gross Cash Farm Income (GCFI)[2]. Previous versions only used annual sales income. ERS recently updated the typology to reflect three important trends: commodity price increases, a shift in production to larger farms, and the rapid growth of the use of production contracts among livestock producers

For PAIL's purposes the relevant categories are derived from (Hoppe and MacDonald, 2013):

1. Small Family Farms, GFCI less than $350,000
2. Mid-size Family Farms, GFCI between $350,00 and $900,00
3. Large Scale Family Farms, GFCI greater than $1,000,000
4. Large Family Farms, GFCI of $1M - $499,999
5. Very Large Farms, GFCI of $5M or More
6. Non-Family Farms (includes Corporate Farms and Cooperatives). GFCI level is not specified. Defined as any farm where the operator and persons related to the operator do not own a majority of the business.

The previous version (2001) of the typology included large farms, with sales between $250,000 and $499,999, and very large family farms, with sales of $500,000 or more. However, farm production is shifting to much larger farms, thus the additional category of Mid-size family farms and the much higher levels of GCFI. Farms that annually generate $250,000 plus in sales represent just 10% of the nation's farms, but account for 82% of U.S. food production (CNN Money, Nov 2012).

Due to the size of investment (both time and money) to deploy an integrated solution, the *ideal* target customer for a level 2 or 3 Integrated Ag Irrigation solution is the Large Scale Family Farm or the Non-Family Farm. Mid-size Family Farms who are early adopters may also be targets, but would likely need large incentives as part of purchase. Small Family Farms are more likely to adopt the Level 1 solution, if they are to make a change.

In addition to the definitions above, the ideal target customers have one or more of the following characteristics:

1. They have a requirement or compelling need (either through natural causes or government regulations) to reduce irrigation water use.
2. They must manage multiple brands of equipment, especially center pivots.
3. They already have a level of data management on their farm and employ one or more employees who are dedicated to data management and integration.
4. Their overall attitude toward farming technology is forward thinking.
5. They are required by their local government, utility or crop insurance provider to report applied irrigation and/or chemigation.
6. They are already ready to purchase new irrigation capital equipment.

For the grower, the opportunity is to increase profitability through lower energy use and reduced costs with the availability of an integrated, easy-to-use decision support solution that uses a flexible approach combining optimal irrigation techniques with well-integrated soil, moisture, and weather data. The AG IRR initiative offers opportunities for cost reduction in energy, fertilizer and the

[2] GCFI includes the farm's sales of crops and livestock, receipts of Government payments, and other farm-related income. Gross farm sales, in contrast, exclude other farm-related income and include items than are not revenue to the farm: the value of sales accruing to share-landlords and production contractors and Government payments accruing to landlords.

associated labor expenditures. In-stream water requirements limit the amount of irrigated land development and water efficiency may drive more acreage development.

The irrigation data standards can also be seen as part of a larger set of data standard requirements. Growers are seeing an increasing need to integrate distinct sets of farm data. Merging precision farming technologies offer advantages in identifying, managing and tracking their products. However, given the lack of data standards and interoperability between manufacturers and suppliers, they also create significant challenges as dissimilar products and platforms multiply.

Allan Fetters, Director of Technology at J.R. Simplot Company and a PAIL team member, agreed with McDowell. “Growers are inundated with data. We have diagnostic and performance data coming in from each piece of equipment we use, on each and every field of the farm, let alone what and where all the crop inputs are being applied. This is compounded especially if you are running a mixed fleet of equipment,” he explained. “Each source of data received on the farm is displayed in its own configuration, on its own site, so a lot of extra time is being spent trying to analyze this data and interpret it into useful information that is going to make the farmer more productive. We need a free flow of data to enable us to farm with the best real-time data available. Ideally I would have all of my key farm data and digital decision making accessible through one common, easy to use dashboard, so I can control, manage, troubleshoot, view, and analyze my farm data.”

Complex Systems Market Model

Developing and aligning to a set of data standards is a critical component of a larger system that must be configured before an integrated solution actually reaches the market. Unlike individual soil sensors or field weather stations, which are high volume sales, the AG|IRR solution is a complex systems market model.

Figure 2 below shows an adaptation of Geoffrey Moore’s model for complex systems (Moore, 2005), as applied to an agricultural irrigation system.

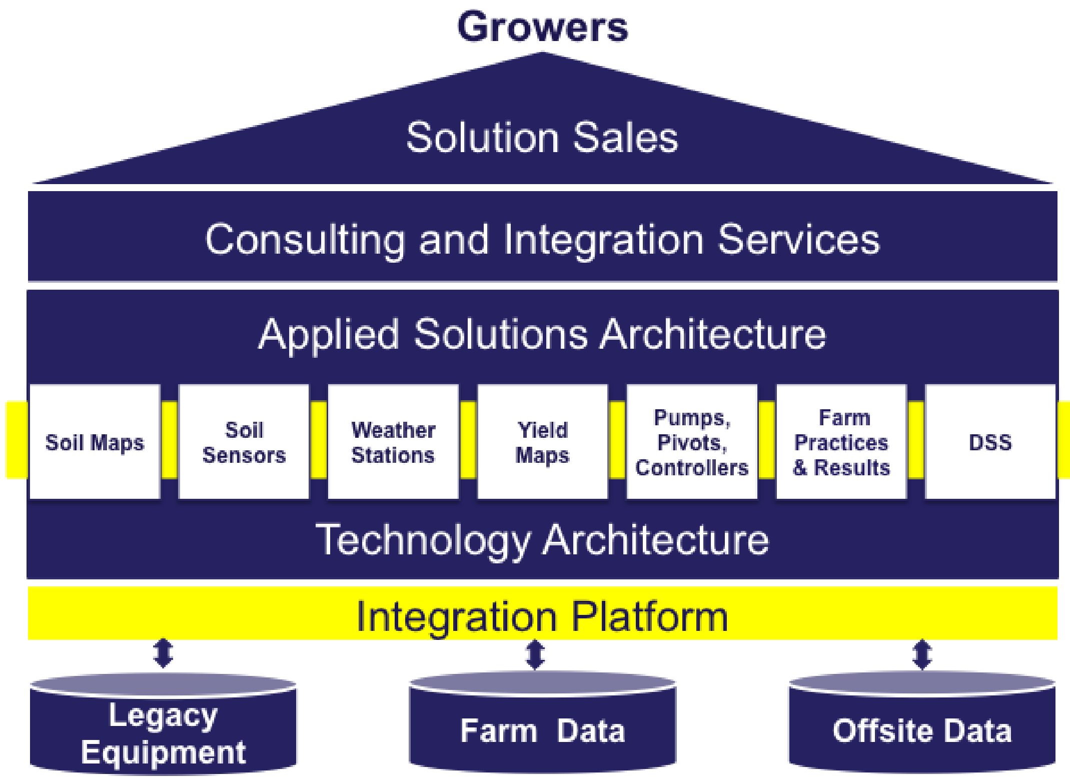

Figure 2 Complex Systems Market Model

The model is organized around the grower because market success is dependent upon a relatively small set of customers making relatively large purchase commitments. Qualified customers are the scarcest resource in the system. They typically have the power in sales negotiations, and solutions must be customized to fit within their existing farm management processes and equipment infrastructure. No two solutions are identical. Lead times are long.

Solution Sales can be driven from a local sales source, such as an irrigation equipment retailer, or in conjunction with a consulting service. Irrigation consultants can either work directly with growers or vendors. In some cases, they may be tied directly with a particular pivot or irrigation services provider. Their role is to bridge the specific needs and requirements of the grower and the core capabilities of the Ag Irrigation solution.

Two sub-architectures surround a set of multiple, disparate elements. These elements are modules that can be used to provide the system's ability to generate irrigation prescriptions and to monitor and report the results. Different vendors often supply them. The system is extensible: new modules can be added. And the system can integrate with other FMIS systems if necessary or desired.

The technology architecture unifies the system on the systems-facing side. It includes common facilities and protocols, such as the PAIL data standards and data transfer mechanisms. It would also include the business rules for those data standards. The technology architecture enables disparate elements to be swapped in and out to create different solution sets, without having to reconstruct everything from the ground up.

The solution architecture unifies these elements in a way that is clear and actionable by the grower. It consists of application specific templates that align the generic Ag Irrigation solution with the specific grower's needs. It embodies business and farm processes that are specific to that grower, and communicates the business results of the applied application. It is also understandable and sellable by the consultants and system integrators, as well as the solution sales force. It includes the user interface, as well as instructions and training.

The bottom layer indicates what the grower already has in place: pivots and other equipment, a local database, as well as offsite data, such as SSURGO soil maps or Agrimet weather forecasts. Above that, the Integration Platform provides a buffer that is familiar to the current generation of farm managers, has proven reliability, probable longevity, and is predictable in its interactions with the equipment and systems with which it interfaces.

No one member of the value chain can deliver all the products and services end-to-end. Typically this requires a company that has a reputation in the solution space that gives it permission to lead, bringing in value-added partners who can complete the solution model.

The PAIL Project

The goal of the Precision Agriculture Irrigation Leadership (PAIL) Project is to improve agriculture irrigation by developing a common set of data standards and formats to convert data for use in irrigation data analysis and prescription programs.

"Ultimately, the objective of this project is have a common set of data standards and protocols used across the agriculture industry," says Terry Schlitz, AgSense President and Chair of AgGateway's Water Management Council. "With those in place, industry can deliver much more efficient, easy-to-use solutions for producers, which in turn will help them use available water and energy more effectively."

Producers and manufacturers currently report that it is difficult and time-consuming to make decisions on how much water to apply when and where. That's because weather, soil moisture and other relevant data are stored in a variety of Original Equipment Manufacturer (OEM) formats and data sources.

"Growers have many more options now to irrigate their fields more effectively," said Andres Ferreyra, AgGateway Precision Agriculture Council Chair, and AgConnections research and development coordinator. "For example, they can invest in soil maps, install different types of pumps or flow meters, use soil moisture sensors, and put variable rate irrigation systems on their center pivots. There are a few software applications that tie them together. However, these tools don't actually talk to each other effectively or efficiently."

Project Plan and Progress

The PAIL group officially began work in early 2013. A summary of the planned steps are shown in Figure 3. The project to have two parts. The first will focus on specifying the standard. The second phase will focus on testing and implementation, expansion of the standard to include other uses of irrigation technology, and inclusion of emerging issues. Specific deliverables of the first phase are:

- Use Cases - These will describe most (or all) of the likely scenarios where systems will use the data standards. The use cases also help to define the scope of the data standard.
- Glossary - a robust dictionary of terms and definitions as they are used within the context of specifying the data standard.
- Ontology - a technical specification of each of the quantities and variable referenced in the standard. The ontology uniquely identifies each of the variables referenced in the project.
- Schema - a technical document that unambiguously specifies all of the potential information, its structure, and interrelationships. This document is the basis for creating, verifying, and using documents and messages that conform to the data standard.
- A test of the standards wherein the standard's function and completeness are verified within the context of an integrated irrigation management system
- A proposed standard submitted to the American Society of Agricultural and Biological Engineering

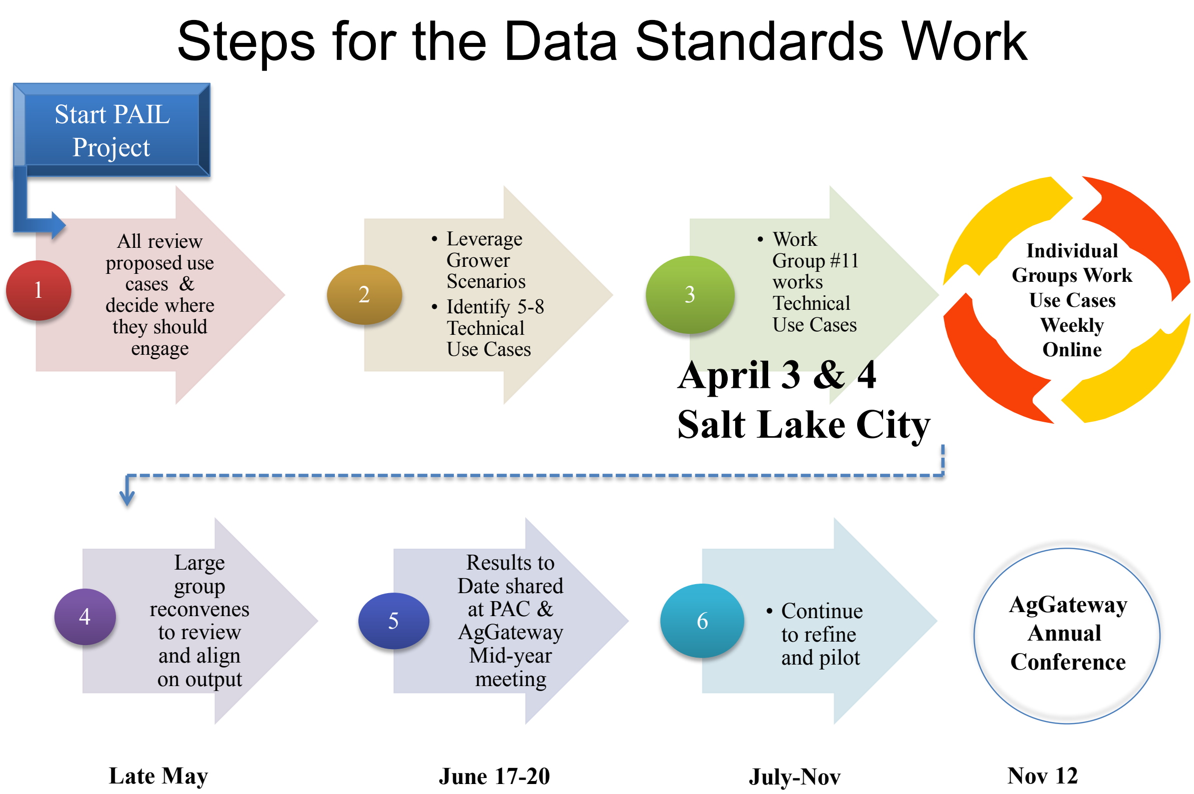

Figure 3 The PAIL Data Standards process

Significant progress has been made on the Use Cases that will fully define the scope of the data standard. A broad definition of the PAIL scope is included in the PAIL project charter. The scope is included below.

In Scope

1. Irrigation system (not restricted to pivots) setup, configuration, performance specification
    1. Location and geometry of the irrigation system
        1. Opportunity to discuss end gun, corner arm specification
    2. Flows and pressure
2. Irrigation system operation, control, and status
    1. Schedules (how much and when) and Prescriptions (where)
        1. Data representation for establishing a schedule / prescription's scope in space and time
    2. Error reporting, Alerts
    3. As-applied / resource use accounting (non-economic)
3. Pumping Plants
    1. Setup & Configuration
    2. Monitoring & Control
4. Data acquisition systems (Observations. Source is on-farm)
    1. Setup & Configuration
    2. General environmental monitoring
    3. Soil monitoring
    4. Atmospheric monitoring
    5. Plant-based monitoring
5. External Data Inputs (Offsite, weather networks, etc.)
    1. Weather Forecast, aggregated weather / climate info, weather networks
    2. Soil (SSURGO and other soil maps, EC maps, holding capacity maps, etc.)
    3. Energy
    4. DEM
    5. Historical Yield Data (Explore cooperation w SPADE)
    6. Manual Soil Sampling
    7. Crop Performance, Crop coefficients
6. Data Outputs
    1. Historical Weather summary
    2. Yield analysis
    3. Water balance (e.g., NRCS IWM reporting)

Out-of-Scope

1. Data exchange below the OSI (Open Systems Interconnection) Transport Layer, corresponding to the International Standards Organization (ISO) 7498 standard.
2. Crop simulation details
3. Biotic factor scouting details.
4. Considerations / recommendations about sampling rates.
5. Crop performance: Yield modeling
6. Human-mediated data acquisition (e.g. scouting)
    1. Stand density, quality, growth stages
    2. Abiotic stress factors, such as water and flooding
    3. Biotic stress factors, such as insects and diseases
7. Economics (energy use, energy cost, water costs, revenue forecast (estimated yield & price), estimated costs of other production practices (fertilizers, crop protection).

Organization

The preceding scope statement includes a broad variety of information sources and types. Accordingly, the PAIL participants also represent a diverse group of technologies. Companies producing Farm Management Information Systems, Pivot Irrigation Systems, weather and environmental monitoring equipment, soil moisture monitoring equipment, and a few large growers are participating in the PAIL project.

AgGateway

AgGateway (www.aggateway.org) is a non-profit consortium of approximately 200 companies of the agriculture industry. Its mission is to promote, enable, and expand eBusiness in agriculture. AgGateway member companies work on projects within nine industry segments, including Ag retail, crop protection, crop nutrition, seed, grain and precision agriculture.

The irrigation data standards work is happening within the Water Management Working Group, part of AgGateway's Precision Ag Council. In November 2012 the companies that had previously been working on data standards development with NEAA agreed to move the standards development effort into the AgGateway environment, to benefit from AgGateway's anti-trust umbrella, to benefit from AgGateway's existing infrastructure and standards development and maintenance services, and to benefit from the synergies that could arise from exposure to a larger group of businesses committed to data exchange standards. As a result, AgGateway's Precision Ag Council chartered the PAIL (Precision Ag Irrigation leadership) Project in early 2013.

Northwest Energy Efficiency Alliance

The Northwest Energy Efficiency Alliance (NEEA) is a non-profit organization working to increase energy efficiency to meet our future energy needs. NEEA is supported by and works in collaboration with the Bonneville Power Administration, Energy Trust of Oregon and more than 100 Northwest utilities on behalf of more than 12 million energy consumers. NEEA uses the market power of the region to accelerate the innovation and adoption of energy-efficient products, services and practices. Since 1997, NEEA and its partners have saved enough energy to power more than 600,000 homes each year.

Workgroups

Given the breadth of information covered by PAIL's scope, it is impractical to have the entire group address the entire scope simultaneously. Instead three sub groups have been formed: Inbound data sources, Field Operations, Setup & Configuration. A conceptual representation of these groups is shown in Figure 4. The scope of the different groups illustrates the collaborative development process used in PAIL. The work groups were not defined *a priori*. The groups evolved out of several of the PAIL group meetings. The different company representatives whose products interacted or performed similar functions gravitated together to focus on data exchanges that their products were likely to perform. Not only does this partitioning provide a practical decomposition of the scope, it also provides a convenient way for new participants to find the right workgroup for their participation.

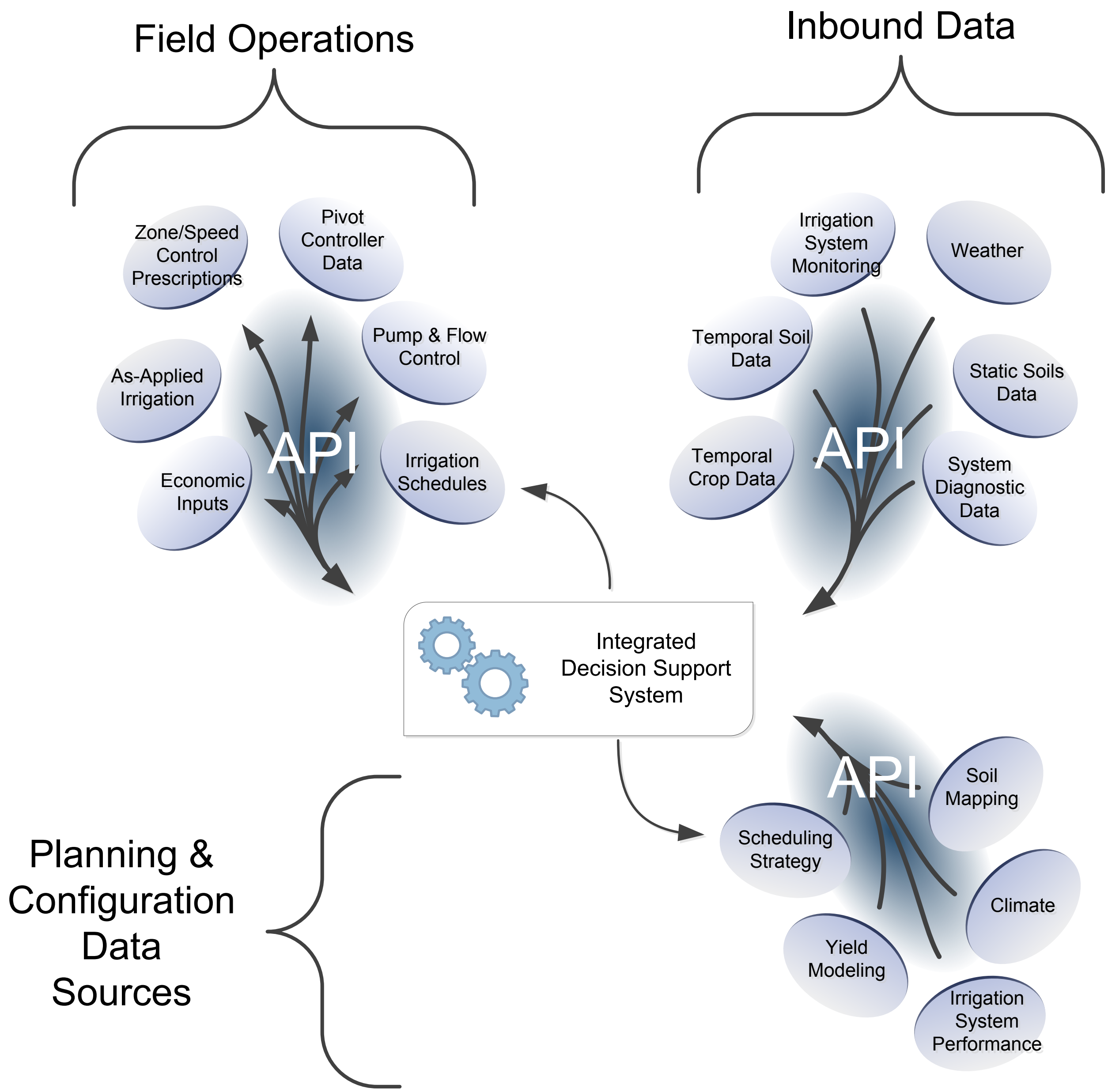

Figure 4 Conceptual representation of PAIL work groups

Conclusion

System integration is a significant factor in ease of use of advanced technologies. Adoption of new irrigation technology is limited by the effort required to use the technology. The Precision Ag Irrigation Leadership project is expected to have a lasting beneficial impact on the agricultural irrigation industry. PAIL will improve interoperability of irrigation technologies and, consequently, increase adoption of more efficient irrigation practices. This paper has described the goals, structure, and progress of the Precision Ag Irrigation Leadership project. The PAIL project is ongoing and the workgroups expect to complete their goals in 2014. Plans for the second phase, PAIL 2, are already underway. Companies, institutions, and organizations interested in participating should contact the authors for instructions on how to join AgGateway and how they can contribute to this effort. As of November 2013, membership in the PAIL project is still open to new participants; it requires membership in AgGateway, and membership in the PAIL project. Interested parties should contact AgGateway Member Services (member.services@aggateway.org) for more information.

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Evaluating Water Treatment Technologies to Irrigate Crops With Saline Groundwater

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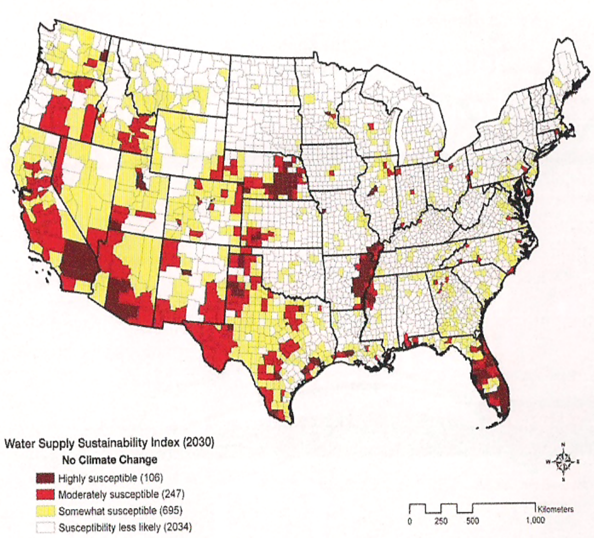
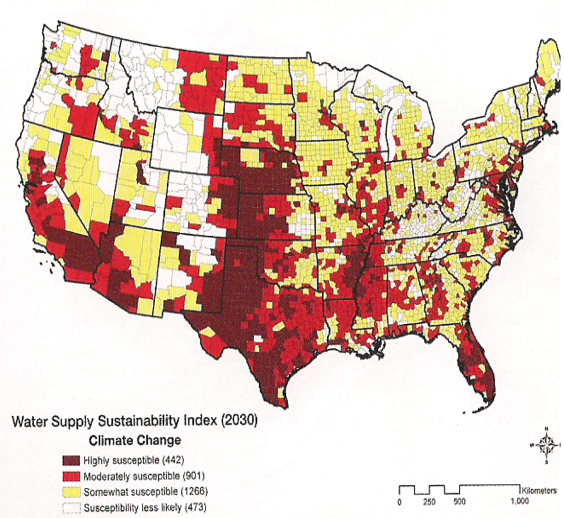
Abstract

Since the 1950's many irrigation experts have reported that low saline groundwater is a vast and underutilized resource in agriculture and that low cost energy water treatment technologies would be needed for its use in irrigation. Over the years, advanced treatment technologies have arisen to increase the benefits from the use of electricity and electromagnetic fields in non-chemical water conditioning or treatment applications along with farmer anecdotal information on crop benefits. However, standardized test protocols have not been developed that could directly measure and validate effectiveness to the marketplace. Over the past 2 years, paired crop production test trials were conducted in Arizona, California, and Texas with treated and untreated (control) low saline groundwater for irrigation of crops to develop standard test protocols. Tests were designed to measure: seed germination, root hair growth, plant growth, seed and seed pod development, plant survival due to drought and exposure to high temperatures in field trial test sites, and subsequent changes in salt cations and nitrogen levels.

FUTURE WATER SUPPLY AND DEMAND

During the 20th century, the global population increased 300 percent while demand for freshwater increased 600 percent. The world's water consumption rate is doubling every 20 years, outpacing by two times the rate of population growth. By 2025, global water demand will exceed supply by 50 percent, due to persistent regional droughts, shifting of the population to coastal cities, and industrial growth. Some regions in the US have seen ground water levels drop as much as 300 to 900 feet over the past 50 years and with no future pumping full recharge is likely to take centuries to millennia.





The above maps are of the calculated Water Supply Sustainability Index for the year 2030 with and without Climate Change Impacts plotted (NRDC, 2010) illustrating the significant impact that climate change will have on the sustainability of water supplies in the coming decades for the middle states of the US. The analysis by Tetra Tech integrating 7 soil and atmosphere moisture models examined the effects of global warming on water supply and demand in the contiguous United States

Impact of Droughts:

Droughts have a natural component that increases freshwater shortages. Floods have minimal benefits because they destroy homes, businesses, infra-structure (e.g., dams, mud slides), farm animals, and crops, where as droughts add uncertainty to rainfall patterns. While freshwater supplies remain relatively flat and water use efficiency improves about 1 percent per year, population growth has soared post WW-II.

Since World War II, advances in irrigation technologies have allowed farmers to extend America's breadbasket through the entire Great Plains, transforming "The Great American Desert" into an expanse of green circles defined by the reach of central pivot irrigation systems. That groundwater for irrigation comes from the Ogallala Aquifer, a massive underground lake that stretches from southern South Dakota through northern Texas, covering about 174,000 square miles.

The Ogallala Aquifer is being drained at alarming rates, and some places have already seen what happens when local levels drop below the point where water can no longer be pumped. When combined with regional droughts and future climate shifts, these water shortages can only expedite the need for low cost energy water treatment technologies for saline ground waters.

Droughts and floods already complicate the prediction of widespread freshwater shortages and should Global Climate Change extend the duration, magnitude, and frequency of droughts and floods, then the water shortages and effects will greatly increase. With increased demand, extreme droughts greatly exacerbate freshwater shortages.

Agriculture, a critical component of the US economy and food and fiber supply, is the major user of ground and surface water in the US accounting for approximately 80 percent of the Nation's consumptive water use and more than 90 percent in many Western States. Groundwater is rapidly becoming more expensive to pump from increased depths. These water shortages have brought about the need to accelerate the development of new freshwater sources, expand reuse, recycled, and the use of more treated saline waters.

For much of the past decade, California has experienced a series of droughts impacting municipal water supplies and putting at risk more than 1/3 of the US food supply that is produced there. Future US water shortages will also limit and drive up the cost of food and energy.

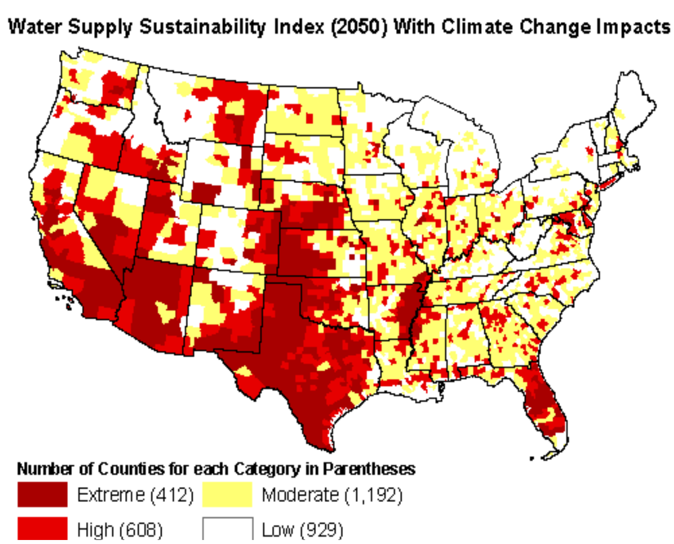
In the US, EPA and USDA for the past decades have focused on the need to reduce water waste by increasing recycling and water use efficiency. Such actions are essential to development of a national freshwater supply management plan but conservation alone is inadequate to solve the problem.

The supply and cost of freshwater is a critical global factor for sustainable development. High water costs impacts every nation’s economy, subsequently preventing them from being able to import goods and services that they need, disrupting global trade and producing a global economic quagmire. An early sign of the crisis will be a rapid increase in the cost of water to reduce use and to keep those freshwater supplies flowing.

Consequences of a widespread freshwater scarcity are far-reaching. Freshwater supply forms the third leg of the ‘economy-energy stool’ and estimates suggest that by 2025 freshwater scarcity will compete with energy as an internationally limited resource.

The continued future depletion of inland and ground water supplies will negate many of the federal and state environmental regulatory gains of the last 50 years: NEPA, CWA, ESA, etc. Freshwater scarcity exists in the arid US West, parts of the South, and now is an issue east of the Mississippi River during periods of drought. Droughts and water shortages have been projected to increase and spread to other regions of the US.

The Map on the right is of the Water Supply Sustainability Index predicted for the year 2050 with Climate Change Impacts, illustrating the significant impact that climate change will have on the sustainability of water supplies in the coming decades. The analysis by Tetra Tech integrating 7 soil and atmosphere moisture models examined the effects of global warming on water supply and demand in the contiguous United States, and found that more than 1,100 counties—one-third of all counties in the lower 48—will face higher risks of water shortages by mid-century as the result of global warming.



Source: National Resources Defense Council. (2010). http://www.nrdc.org/global-warming.watersustainability/

Underutilized & Unmapped Available Low Saline Groundwaters

Groundwater is commonly considered saline if it has a TDS concentration greater than 1,000 mg/L. This arbitrary upper limit of freshwater is based on the suitability of water for human consumption. Although water with a TDS greater than 1,000 mg/L is sometimes used for domestic supply in areas where water of lower TDS content is not available, but water containing more than 3,000 mg/L is generally too salty to drink.

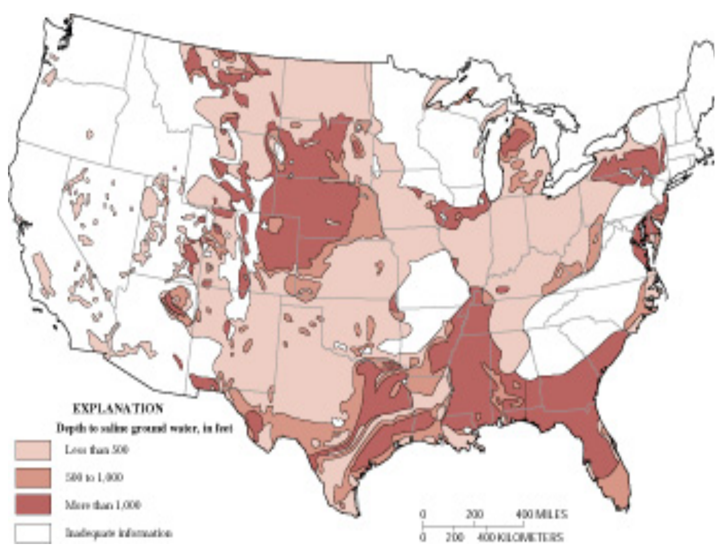
The U.S. Environmental Protection Agency has established a guideline (secondary maximum contaminant level) of 500 mg/L for dissolved solids. Groundwater with salinity greater than seawater (about 35,000 mg/L) is referred to as brine.

Little is known about the areas of most aquifers that contain saline water compared to the areas that contain freshwater, because the ability and the need to utilize saline ground water in agriculture has been limited. Most groundwater resource evaluations have been devoted to establishing the extent and properties of freshwater aquifers, whereas evaluations of saline water-bearing units have been mostly devoted to determining the effects on freshwater movement.

Much of the work to characterize saline groundwater resources in the United States was done in the 1950s and 1960s. Surveys of saline water resources of several States (for example, Winslow and Kister, 1956), and of selected areas within States (for example, Hood, 1963), were published in the late 1950s and early 1960s. Krieger and others (1957) undertook a preliminary survey of the saline water resources of the United States during this period.

Later, Feth and others (1965) prepared a generalized map of the depth to saline groundwater for the conterminous United States. This map provides a preliminary perspective on the location of saline ground-water resources, but provides limited information about critical factors required to understand the development potential of the resources such as aquifer hydraulic conductivity and well yields.

The map to the right presents the depth to saline groundwater in the United States (generalized from Feth and others, 1965), from USGS Fact Sheet 075—03, Oct, 2003.



Saline groundwater's in the US are not desalinated for agriculture because of the expense involved in desalinating these waters by current technologies would be cost prohibitive for there use in irrigation due to the quantities of water needed in agriculture. Development and application of low energy cost technologies that would make these waters suitable for municipal drinking water (less than 500 ppm US EPA Standards) and (less than 1,500 ppm for agriculture (tolerance varies by crop) would greatly increase sustainable economic development and agricultural production in southwestern and western states, and serve as a very useful technology in land reclamation and restoration.

Since the 1950's many irrigation experts have reported that low saline groundwater is an under utilized resource in agriculture. The prohibitive factor has been the salinity and presence of salt cations in these low saline groundwater supplies that place osmotic stress on plants.

New Water Conditioning Devices

The controversy and historical negativity associated with the use and benefits of electricity and electromagnetic fields in non-chemical water conditioning or treatment applications for low saline ground water is extensive. Many investigators have examined the effectiveness of these systems with mixed results. Welder and Partridge (1953), Wilkes and Baum (1979) and Limpet and Arber (1985) presented reviews of operating principles and claims for similar "new generation water conditioning devices." Hunter (2002) provides a similar review for currently available commercial devices, their proposed mechanisms of operation, review of the literature for valid scientific evidence of effective results in laboratory and field application and testing to provide comparative evaluations of comparable technologies to treat scale in water cooling towers.

A peer review paper written by Huchler (2002) presents an overview of the numerous systems using combinations of electrical, magnetic and mechanical means to replace water treatment chemicals. This paper describes devices marketed prior to 2002, their proposed mechanisms of operation, review the literature for clear evidence of effective action in laboratory and field applications and provide recommendations for evaluation in cooling towers where they are primarily used to prevent scaling. The intent of the Huchler paper was not to refute or corroborate claims by manufacturers about the effectiveness of the different devices, but rather to provide:

- An introduction to the current technologies and devices used in cooling and boiler systems,
- Provide descriptions of the mechanical and electrical principles by which they operate,
- Discuss possible mechanisms for action,
- Describe situations in which clear evidence of effective action is demonstrated in lab and field situations, and
- Provide recommendations for evaluating the claims of these devices in field situations.

For several decades people have been looking for a technology to solve problems of deposits of minerals (scaling) in water pipes and pumps. The history of non-chemical water treatment systems (NCWTS) to reduce or eliminate the impact of minerals found in hard water is long and controversial, marked by many claims for and against the effectiveness of NCWTS (Huchler, 2002).

Non-chemical Water Treatment System Terms and Descriptions

There is no single term is used that describes all of these devices. The awkward term "non-chemical water treatment systems" describes a host of technologies including magnetic, electromagnetic, electrostatic, and AC induction. Welder and Partridge (1953) used the term "water conditioning gadgets"; Wilkes and Baum (1979), the term "water conditioning devices." "Physical water treatment" and "electronic water treatment" are also general terms currently used by some proponents of these devices.

Many investigators have examined the effectiveness of these systems with mixed results. Welder and Partridge (1953), Wilkes and Baum (1979) and Limpet and Arber (1985) presented reviews of operating principles and claims for similar "new generation water conditioning devices." Hunter (2002) provides a similar review for currently available commercial devices, their proposed mechanisms of operation, review of the literature for valid scientific evidence of effective results in laboratory and field application and testing to provide comparative evaluations of comparable technologies to treat scale in water cooling towers.

The science of magnetic water treatment is poorly understood as the technologies have evolved by trial and error over the past 20 years and its application for the prevention of scaling and corrosion in cooling towers is debated by two camps, Donaldson and Grimes (1988), and Raisen (1984) have reported positive results from published field studies. However, if one conducts an in-depth search of the literature, one may not find ever one published peer reviewed paper developing specific protocols for testing the effectiveness of any of these technologies, as you would find published by ASTM.

So in the near future, if a farmer is forced to use low saline ground water because of droughts, the problem is how to select the most effective (increase crop production per acre, reduce irrigation water use, reduced fertilizer and nutrient use, increase the health of plants, increase disease resistance, and provide low energy cost COTS (Commercial Off-The-Shelf) technology that can be used to treat low saline ground water and make salt cations less available to plants.

TransGlobal H2o, LLC (TGH2o) in Houston, TX approached me in the fall of 2011 to develop standardized testing protocols to measure the effectiveness of their COTS water treatment technologies for the utilization of low saline groundwater to irrigate crops grown in saline soils in arid regions. The studies began in 2012 with barley (AZ), and added other crops: spinach (CA), greenhouse tomatoes (CA), and pecans (TX), with the following to be developed in the fall of 2013: carrots (CA), and strawberry's (CA), and in 2014 cotton (TX). These field tests were developed as Cooperative Farm Demonstration Projects to prove the benefits of the technologies to large farm enterprises the benefits of the technology as part of TGH2o's ongoing R&D and its marketing strategy.

METHODS AND MATERIALS

In the barley-paired field trials (2012), the following test protocols were utilized:

- Paired Field Trials were irrigated with treated (TGH2o technologies) and untreated (controls) local low saline groundwater (1,500 TDS) for barley seeds in the trails.
- Barley seeds were planted in rows in the designated treated and untreated test plots and the subsequent seed germination, root growth and plant growth data were collected from treated and untreated rows and photographed weekly to determine the plant maturation rates, plant production rates per acre, and subsequent economic benefits.

Paired Field Tests in 2012 to the Present

This past year, paired (replicate) test trial protocols were developed and initiated with treated and untreated (control) low saline groundwater to irrigate spinach (CA) greenhouse tomatoes (CA), and pecans (TX) with TGH2o LLC technologies.

The objectives of these trials were to determine if specific anecdotal information associated with crop benefits that farmers had identified over the past 18 years from using TGH2o water conditioning technologies (Advanced New Patents Pending) could be scientifically measured, and if the physical, chemical and biological processes - mechanisms influencing the effectiveness of this treatment technology, could be determined and optimized.

SUMMARY OF THE RESULTS (Completed 2012 Studies)

As summary of the results (crop benefits) comparing the results defined as crop benefits from barley paired field studies conducted in 2012 under the standardized paired field tests in large field plots from the use of treated and untreated (control) irrigation water:

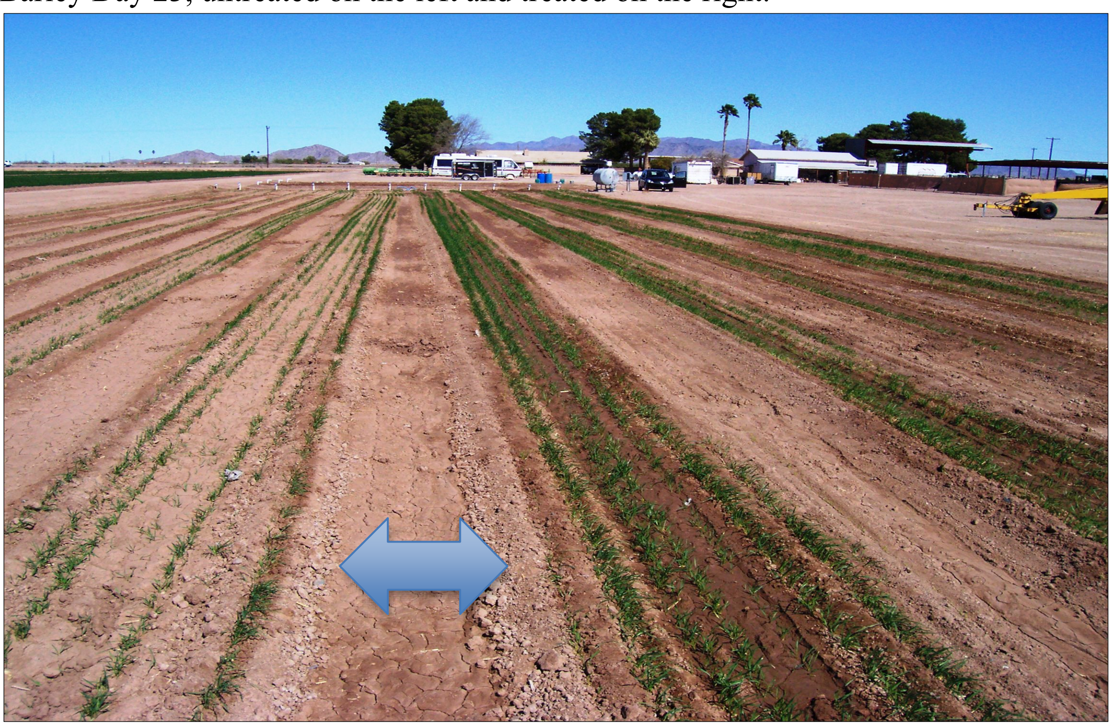
- Faster seed germination ~ 5-7 days – and development of root hairs.
- More seeds germinated ~5 times per unit area.
- Faster root growth ~ 5-7 days. Faster plant growth and leafing out.
- More plants survive seed germination and faster growing plants, more leaves
- Taller plants (2x) bigger leaves, healthier and greener plants
- Faster seed pods germination and seed development in seedpods ~10 days.
- More (1.5x) seeds produced per seedpod.
- Significantly reduced plant death (from osmotic stress) from plants irrigated with Treated water than those irrigated with Untreated water subjected to a two inch rain fall that dissolved into solution soil surface salts deposits from the Untreated water.
- Significantly reduced plant death (desiccation) due to exposure to heat from high air temperatures (112°-118 °F) and in period of high-dry winds in test sites irrigated with Treated water.
- Increased development of nitrogen fixing bacterial and nitrogen levels in soils treated with Treated irrigation water.

To provide visual data of the above results, from these paired field trials, a next series of photographs are presented from the barley (AZ) paired test plots (side-by-side) for the indicated specific stages of plant development and crop production.

Barley seeds Day 7 Following Planting: Germination rate differences. The photograph is of germinating seeds removed from rows watered with treated and untreated (controls) irrigation water that was planted on 2.9.2012 with weekly irrigation.

The right top pair of barley seeds is from untreated irrigation watered rows and show minor development. The three seeds with root hairs are from the rows that were irrigated with treated water. These seeds have begun germination and the formation of root hairs.

Barley Day 23, untreated on the left and treated on the right.



The plants on the right have been irrigated with treated water and have retained some of this water at the surface almost 36 hours longer than those watered with untreated water on the left of the blue arrow, indicating that the treated water has greater surface tension, cohesion and adhesion, less water loss (vaporization) providing more water to the plants on the right.

Barley Day 62: Untreated on the left and treated on the right. Notice: Untreated on the left are not surviving osmotic stress when compared to the plants irrigated with treated water on the right.

Barley Day 62: Close up photo of plants that survived in the untreated rows (left) and the treated rows (right). Notice: In the photo on the left, the row irrigated with untreated water that plant maturation and growth from seeds significantly reduced in density over the width of the row and height (~9 inches), and in the row irrigated with treated water and the plant density is far greater and plant height (~20 inches).

The same kind of results have been found with several varieties of spinach in the studies conducted in California, which found an increase of 15.7% to 17.5% in crop production per acre for an approximate gain of $1,700 per acre. A study in Mexico green houses found over 20% increase in pounds of tomatoes produced in high (9,000 TDS) saline groundwaters. Some preliminary studies with cotton on desert land in AZ where 2+ bales per acre would be considered a good crop using 1,500 TDS low saline water in ditch irrigation achieved almost 5 bales per acre, or approximately 100 boles per linear foot of row.

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Evaluation of RDI™ Precision Irrigation

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Abstract: *Irrigation faces many challenges as the world's resources come under more pressure. Some of these challenges include availability of fresh water, energy to deliver and labor to operate and manage. Precision irrigation via various forms of drip and mechanized irrigation, such as center pivots and linears, are addressing the resource pressures well, but opportunities for improvement still exist. Each has some limitations such as water quality, ability to effectively irrigate irregularly shaped fields, energy requirements, and management expertise required, to name a few. This paper will discuss Valmont® Industries' work to evaluate the potential of a new form of irrigation Valmont is calling Root Demand Irrigation™ (RDI). This new type of subsurface irrigation system depends on the plant to release irrigation as needed from non-coated, non-woven, porous tubes. In addition, the proposed delivery system is expected to operate at very low pressures and have minimal filtration requirements. This paper will detail the first two years of field evaluation of the potential of RDI™.*

Keywords: Precision irrigation, plant roots, sub surface irrigation-

Introduction:
Irrigation to meet crop water requirements has been used for thousands of years. To provide for the needs of an ever expanding world population and shirking availability of resources, many advances in the methods of applying irrigation have occurred. In the last fifty years, the changes have been rapid with the introduction of the center pivot and linear mechanized machines and drip irrigation. Much has been discussed about modifying the root environment (Arkin, 1981). These forms of irrigation have continued to develop toward the more precise application of water for plant production. While the mechanized and drip forms of irrigation are overall doing a good job, there may still be other opportunities to improve the irrigation delivery system. Center pivots and linear are a very economical delivery system, but may not meet farmer needs to irrigate small irregularly and oddly shaped fields. Drip irrigation buried can be very efficient, but has limitations due to costs and required water quality. Both types of irrigation require good management practices to work well, but there appears to be opportunities for improvements in the irrigation delivery system.

Objective:
The goal of this project is to evaluate the potential of another form of irrigation, which relies on the plant roots to release water for meeting the water demands of the plant.

Discussion:
In a continuing effort to better provide for precision irrigation, Valmont Industries looks for improvements to center pivots and linears and the potential for other forms of irrigation. In 2011, Valmont became aware of a potential new technology for irrigation based around a non-coated, porous, non-woven tube that releases water based on the

plant. The basic theory is the tube holds the water at a pressure just below what would break the surface tension of the water. Surface tension is broken by root exudates and water flows from the tube into the root system (Nobel, 1983). Root exudates include the secretion of ions, free oxygen and water, enzymes, mucilage, and a diverse array of carbon containing primary and secondary metabolites.

Root exudation can be broadly divided into two active processes. The first is root excretion of waste materials, and the second is secretion of compounds with known functions such as lubricants and defense (Bais, 2006). It is the second type of exudates that will break the surface tension of the water and release it for plant use. Utilizing the plant system to control the release of water could change how irrigation is approached. Today all forms of commercial irrigation depend on the soil acting as a reservoir to store water to meet plant needs (NRCS National Engineering Handbook). With RDI, the theory is to continuously have water available for the plant rather than going through wetting and drying cycles of the soil.

A plan for testing was designed to evaluate a non-woven, non-coated porous tube's potential to irrigate a crop based around the concept of Root Demand Irrigation. The basic plan was to test a basic concept and if success was seen then move onto larger tests with additional parameters.

Results:

Florida Phase I – Fall 2011

- Goal - determination of basic characteristics of the tube
- Success – defined as relatively uniform delivery based on a crude test
- Area - ~ 0.10 acres
- Plan –
    - Water source – well
    - Filter - none
    - Soil - sand
    - Lay tube on the soil surface with minimal elevation change
    - Space lines 30 inches apart x 800 feet long
    - Operating pressure – 2.1 PSI
        - This pressure was just above the point of breaking surface tension to encourage flow
    - Pressure controlled with a head tank
- Crop - none
- Measurements
    - Pressure at the beginning and end of tubes
        - Measured with a manometer tube
    - Flow at 100 foot locations along the tube

    - Measured with trays placed under the tube

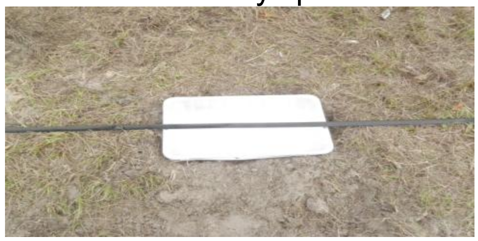

Figure 1. Test setup

- Success – best as could measure met expectations
- Comment – Interesting phenomenon noted was touching the tube would increase the flow. Believe the oils on the fingers were breaking the surface tension and potentially disrupting flow. Made accurate measurements very difficult.

From this trial, we observed sufficient indicators to encourage continuous exploration of the viability of the root demand tube with additional tests.

Florida Phase II – Winter 2011-2012

- Goal - determination how the tube would perform irrigating plants
- Success – defined as maintaining crop growth
- Area - ~ 0.25 acres
- Plan –
  - Water source – well
  - Filter - none
  - Bury tube six inches deep
  - Three lines spaced lines 30 inches apart x 800 feet long
  - Operating pressure – 2.1 PSI
    - This pressure was just under the point of breaking surface tension
  - Pressure controlled with a head tank
  - Plant groups of plants at locations along the tubes
    - One group of ornamentals planted near irrigated plants as a control
- Crop – actively growing ornamental in one gallon pots
- Measurements
  - Pressure at the beginning and end of tubes
  - Flow with Omega flowmeter
  - Soil moisture with Irrometer® WATERMARKs
- Success –
  - Partial success in Phase IIa due to installation not meeting expectations
    - Plants in areas where the lines were collapsed did not grow
  - Fully in Phase IIb when lines reinstalled – 70% of plants grew
- Comment –
  - Installation for Phase IIa was done with equipment that did not meet expectations due to poor depth control
  - Bought a new installation toolbar for Phase IIb which worked controlling depth

- If the plant roots were within the wetted area provided by the tube, then growth occurred; but, if the roots did not reach the wetted area, no growth occurred.


Figure 2. Control system Figure 3. Example of plants

Texas Phase I – Spring 2012

- Goal - determination how the tube would perform in a semi-commercial setting with corn in the corner of center pivots
- Success – defined as crop yields of 80% of center pivot
- Area - ~ 1.5 acres

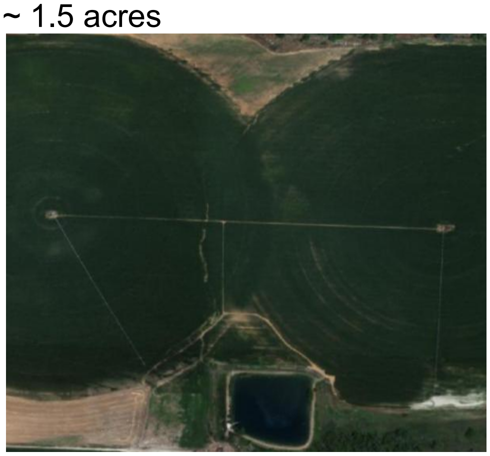


Figure 4. Aerial of field area Figure 5. Plot area

- Plan –
  - Water source – pond
  - None – first challenge to see if the tubes would plug
  - Soil – loamy sand
  - Bury tube ten inches deep
  - Multiple replicated trials including non irrigated
  - Lines spaced at 30 inches apart with lengths of 150 feet to 750 feet
  - Operating pressure – 2.1 PSI
  - Pressure controlled with a head tank
- Crop –

- #2 yellow corn planted at about 32,000 plants per acre
    - Tillage same as under the center pivots
    - Planted at the same time as the center pivots with the rows straight through
    - Slope of three feet maximum across the plot
- Measurements
    - Pressure at the beginning and end of tubes
    - Flow with Netafim™ Fertilizer flowmeters
    - Soil moisture with Irrometer WATERMARKs
    - Yield by hand harvest of areas near Irrometer stations
- Success –
    - Yield of 85% of center pivot

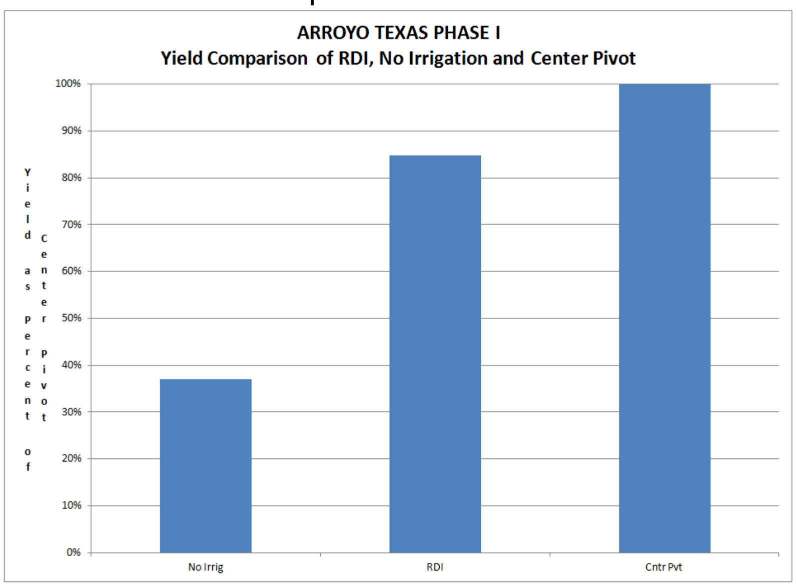

Table 1. Yield information

- Comment –
    - Soil moisture at time of planting was near field capacity to depth of two feet
    - Some weed issues in plots as corner area had not been farmed for several years
    - Far ends of lines run over by farmer limited maximum useable length to 500 feet
    - Did not observe any change in flow along the tube, even though significant moss and algae were growing in the pond

Texas Phase II – Fall 2012

- Goal - determination how the tube would perform in a commercial setting with corn in the corner of center pivots and furrow irrigated
- Success – defined as crop yields of 85% of center pivot and furrow plots
- Area - ~ 4.0 acres
- Plan –

- Moved to a new area in a different corner of the center pivot
- Water source – pond
- Filter - none
- Soil – loamy sand
- Bury tube ten inches deep
- Multiple replicated trials including non irrigated
- Lines spaced at 30 inches apart with lengths of 1,200 feet
- Operating pressure – 2.1 PSI
- Pressure controlled with a pump

- Crop –
  - #2 yellow corn planted at about 32,000 plants per acre
  - Tillage same as under the center pivots
  - Planted at the same time as the center pivots
  - Slope of eight to ten feet across the field
- Measurements
  - Pressure at the beginning and end of tubes
  - Flow with Netafim Fertilizer flowmeters
  - Soil moisture with Irrometer WATERMARKs
  - Yield by hand harvest of areas near Irrometer stations
- Success –
  - Yield of 68% of center pivot – Grade of B-

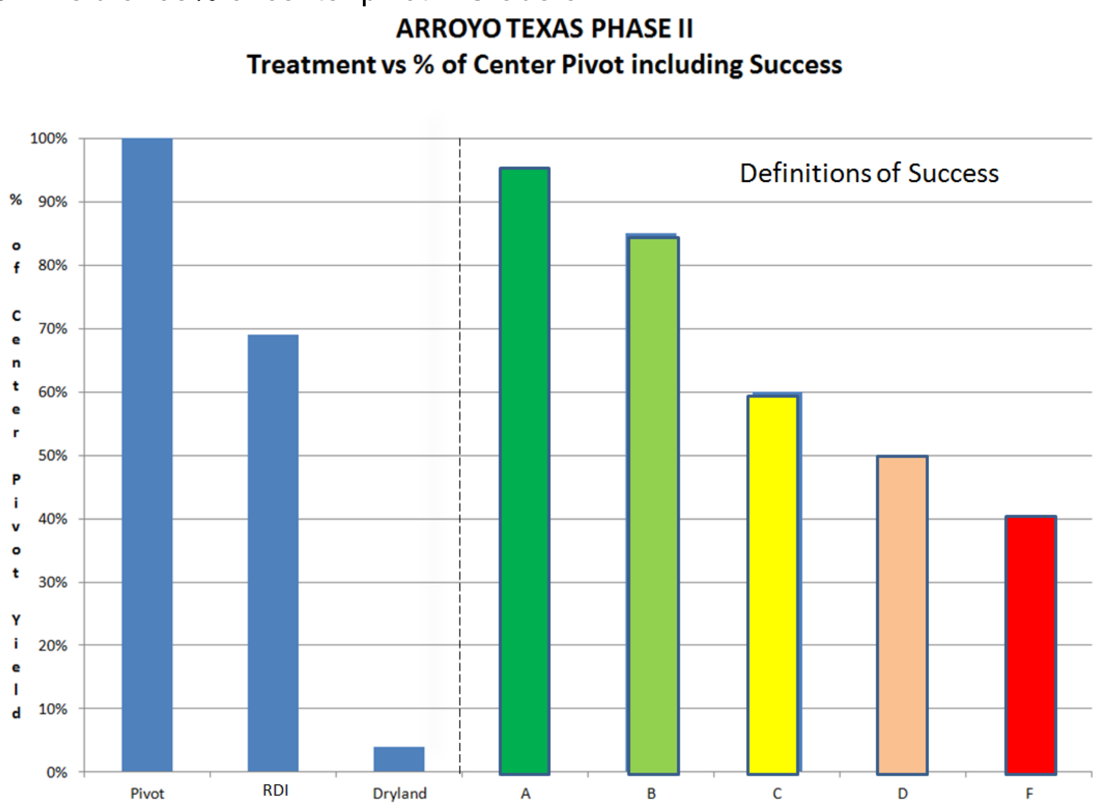

Table 2. Yield vs. success

- Comment –
  - Soil moisture at time of planting was near 50% depleted – it was dry

    - Stand was uneven due to germination delayed until rain about two weeks after planting
    - Some weed issues due to challenges of farmer being able to spray around manometers and Irrometer stations
    - Insufficient water to operate the furrow irrigation plots

Texas Phase IV – Spring 2013

- Goal - determination how the tube would perform in a commercial setting with corn in the corner of center pivots and furrow irrigated
- Success – defined as crop yields of greater than 75% of center pivot and furrow irrigation
- Area - ~ 5.5 acres
- Plan –
    - Slightly larger area than Phase II
    - Water source – pond
    - Filter - none
    - Soil – loamy sand
    - Reinstalled with an improved tube product
    - Bury tube ten inches deep
    - Multiple replicated trials including non irrigated
    - Lines spaced at 30 inches apart with lengths of 1,200 feet
    - Operating pressure – 2.1 PSI
    - Pressure controlled with a pump
- Crop –
    - #2 yellow corn planted at about 32,000 plants per acre
    - Tillage same as under the center pivots
    - Planted at the same time as the center pivots
    - Slope of eight to ten feet across the field
- Measurements
    - Pressure at the beginning and end of tubes
    - Flow with Netafim Fertilizer flowmeters
    - Soil moisture with Irrometer WATERMARKs
    - Yield by hand harvest of areas near Irrometer stations
- Success –
    - Yield of 85% of center pivot and furrow irrigation

Arroyo Texas Phase IV

Treatment	% of center pivot yield	Irrigated	Stand	Plant Health
dryland	14%	no	poor	bad
T3 B1	32%	under	poor	poor
T4 B1	60%	under	poor	fair
T5 B1	63%	under	poor	fair
T1 B4	65%	under	fair	fair
T5 B3	66%	under	fair	fair
T5 B2	86%	ok	good	good
T2 B2	99%	ok	excellent	excellent
T2 B3	99%	ok	excellent	excellent
cntr pvt	100%	well	excellent	excellent

Table 3. Treatments and performance

Measures in corn crop as a percent of center pivot irrigated corn

	RDI	No Irrigation
Yield	78%	14%
Water use	54%	0%
Labor	80%	0%
Crop uniformity	75%	20%

Table 4. RDI performance

- Comment –
  - Again, the soil moisture at time of planting was near 30% depleted – it was dry
  - Stand was uneven due to germination delayed until rain about two weeks after planting
  - Some weed issues due to challenges of farmer being able to spray around manometers and Irrometer stations
  - Biggest challenge was water shortage twice during the crop cycle - once for ten days and again for six days
  - Again there was insufficient water to operate the furrow irrigated plots

Figure 6. Examples of plot crop

Conclusion:
Over the last two years of testing, Valmont has seen sufficient reasons to continue testing and evaluation of non-coated, non-woven, porous tubes as an alternative type of sub-surface irrigation. Strong indications have been seen to show the crop can potentially control at least part of the water from the porous tube to meet crop water demand. Yields from small trials have compared well with the yields from center pivots and other forms of sub-surface irrigation. In addition, the potential has been seen for the Root Demand Irrigation to complement center pivot and linear irrigation by providing a solution to small and/or irregularly shaped fields.

Further work will involve larger field trials and more work to better describe the characteristics, such as uniformity along longer non-coated, non-woven, porous tubes.

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A Demonstration of Energy & Water Savings Potential from an Integrated Precision Irrigation System

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Abstract. Optimal irrigation management is demonstrated on farms in Oregon, Washington, and Idaho, during 2012 and 2013 as part of a multi-year effort to demonstrate the effectiveness and profitability of an integrated irrigation management solution. Integration includes high-resolution soil mapping, variable rate irrigation, on-site ET (estimated), soil moisture monitoring, optimal irrigation methodologies, flow meters, energy use monitoring via smart meters and yield mapping of results. The objective of the demonstrations is to show increased profitability based on optimizing inputs. Initially the information from each of these sources is integrated into a decision support system, Irrigation Management Online, specifically designed to schedule irrigations when water supplies are limited. The management system provides optimized scheduling based on multiple information sources and includes the grower as a critical component of the decision process. This paper will present the results from the 2012 and 2013 seasons and describe plans for following years.

Keywords. Irrigation Optimization, Energy Efficiency, Variable Rate Irrigation, Deficit Irrigation.

Introduction

In the United States irrigated agriculture accounts for approximately 80% of the consumptive use of fresh water. The demand for fresh water is projected to exceed renewable supplies by 2025 (Postel et al., 1996). The world demand for food is becoming greater because of increased population size and growing demand for resource intensive products (beef, poultry, etc.). For irrigated agriculture, at the intersection of these two resource limitations, water shortages will become standard operating conditions. This leads to the obvious conclusion that significant changes must occur, and agriculture, the largest consumer of fresh water, is expected to make big changes in water use. Part of the solution is expected to come from improvements in crop characteristics to reduce water needs and increase stress tolerance (Baulcombe, 2010). However, it is generally recognized that the developing water shortages will also force fundamental changes in the way irrigation is managed (English et al., 2002). Irrigation management will necessarily move from simple stress avoidance (a biological objective) to optimization based on net returns to water (an economic objective). Much more sophisticated irrigation management tools will be needed to support optimal decision-making in a water-limited future. However, the most recent Farm and Ranch Irrigation survey indicated that only 10% of farms used any type of advanced on-farm water management tools (Schaible and Aillery, 2012). This lack of use indicates that technology adoption will be a significant challenge for improving the efficiency of agricultural irrigation.

The complexity of optimal irrigation advisory tools and technologies will require a development foundation that facilitates integration of technologies and information from a variety of sources. These tools will be driven by technologies for environmental monitoring, operational monitoring, and precision irrigation. Adoption of these technologies will, as with any new technology, be limited by its economic viability. The objective of the project described here is to demonstrate the economic potential of optimal irrigation in general and variable rate irrigation in particular.

The Northwest Energy Efficiency Alliance (NEEA) has undertaken a demonstration program that will improve energy efficiency by accelerating adoption of precision irrigation technology. The goals demonstration project are:

- Demonstrate savings in water and energy associated with optimal, variable rate irrigation.
- Determine the cost-effectiveness of current irrigation technologies by balancing the capital investment against financial gains from energy and water savings.
- Determine the relative value of each data source (instrument), both in terms of decision-making power and dollars.
- Provide the foundation for development of data exchange standards and an API for irrigation management.

Optimal Irrigation

Optimality in irrigation can mean different things. A grower could choose to optimize for yield, profit, efficiency, total land in production, or minimum water use. Economically optimum irrigation management is fundamentally different, and more difficult, than conventional irrigation because economically optimal irrigation implies some level of deficit irrigation (English et al., 1990), (English and Raja, 1996),(English and Nuss, 1982). The basic premise of deficit irrigation is illustrated by Figure 1: a production function developed for winter wheat at Hermiston, Oregon. The maximum income occurs when the water application is 16% less that that required for maximum yield. This reduction in water application results in a reduction of crop water use which is the “deficit” in deficit irrigation

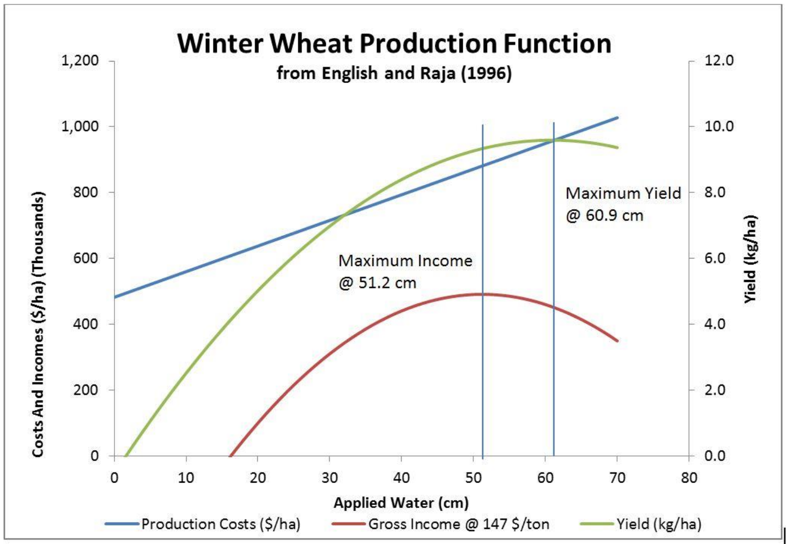

Figure 1 Water Production Function for Winter Wheat

While the conventional paradigm is to irrigate as needed to avoid crop stress, deficit irrigation involves controlling crop stress in spatially variable fields. The conventional method is essentially a balancing of irrigation and ET. Optimal irrigation scheduling is a decision process. The information needed to implement optimal scheduling is orders of magnitude more complex than conventional scheduling. The irrigation manager must account for soil heterogeneity, the spatial variability of applied water and crop responses to water stress. This management complexity is increased when the fields are not managed in isolation; the entire farm is considered when allocating water supplies. For this reason, sophisticated modeling and management tools are needed to implement optimal scheduling.

Irrigation affects and is affected by nearly all farm operations. Limitations on resource availability increase the complexity of the effects on irrigation management. To include these constraints in an optimization algorithm involves codifying the constraints in a manner appropriate for an optimization framework. Encoding all possible constraints is not an achievable goal because all constraints cannot be identified *a priori*. Including most of the constraints would still involve constructing quantitative representations of the different farm processes.

In this initiative, NEEA, working in collaboration with Oregon State University (OSU), uses an OSU-developed system known as Irrigation Management Online (IMO). Instead of building a simulation of the whole (or nearly whole) farm enterprise, IMO takes a different approach. The central thesis of IMO is that the best way to implement or express these constraints is to build a system that includes the only entity that is aware of all these constraints: the grower.

This system, known as Irrigation Management Online (IMO), explicitly analyzes irrigation efficiency and yield reductions for deficit irrigation, performs simultaneous, conjunctive scheduling for all fields in the farm that share a limited water supply, and employs both ET and soil moisture measurements in a Bayesian decision analysis to enhance the accuracy of the irrigation schedules. IMO is described in detail in (Hillyer, 2011), and (Hillyer et al., 2009); the complete details of its implementation are beyond the scope of this paper.

An Integrated Approach

A wide variety of technologies and methods have been developed for precision irrigation management (Smith et al., 2010). The technologies for Center Pivot control have been reviewed by Kranz et al. (2012) and the potential for adaptive control was analyzed by McCarthy et al. (2011). Many of these technologies still operate in isolation. Integrating the information to produce an irrigation schedule requires a significant time investment for the irrigation manager. This systems integration task is part of the focus of the demonstration and the overall project. The goal is to produce a system that demonstrates the potential time and effort savings obtainable from automating the data integration task. Furthermore, the data being integrated will be used to drive the IMO system to produce additional value in the form of more precision for irrigation management. Figure 2 shows a conceptual overview of the data sources that will be integrated.

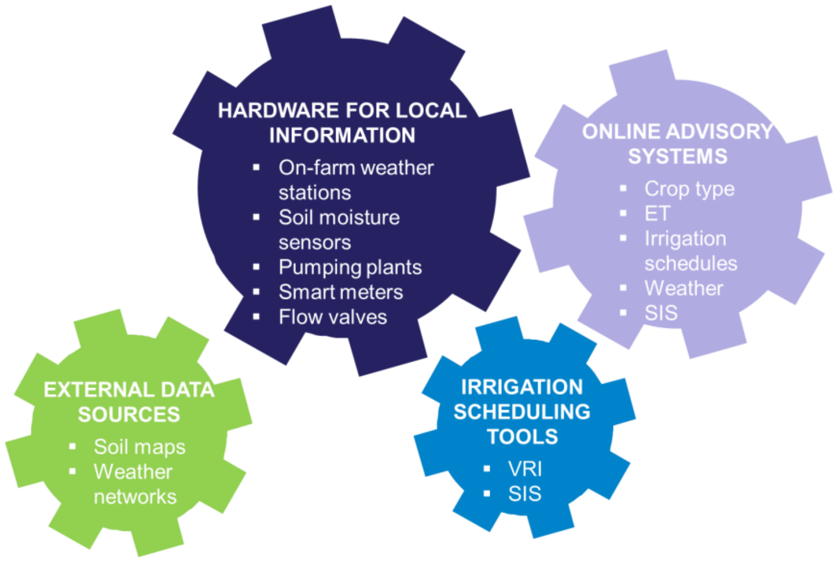

Figure 2 Conceptual overview of the integrated system

Data acquisition is only one part of the scheduling process shown in Figure 2. Making data easy to obtain and presenting it clearly is a valuable feature but the real power of irrigation schedulers lies in the potential for using the information to drive calculations. In this sense, an irrigation scheduler is also a decision support system. Mohan and Arumugam (1997) indicated that Expert Systems are viable and effective tools for irrigation management and stressed the need to include other aspects of irrigation management such as canal and reservoir operation. This need was also indicated by Clyma (1996) who concluded that scheduling services are not adequately integrated with other farm operations that hold greater importance than irrigation decisions.

One of the goals for this demonstration is for the benefits of system integration to transfer beyond the scope of the demonstration project. To that end, development of data exchange standards and an API for irrigation management is being developed in parallel with the demonstration projects. Once the demonstrations are complete, an open source version of the IMO system, including the systems integration features, will be made available. The open source release will serve as an example for other interested developers. Serve as a “guinea pig” for (rather than a competitor to) informing future development of irrigation management systems. NEEA is already collaborating with supply base partners to develop the data exchange standards (see Berne et al, 2013, these proceedings).

Variable Rate Irrigation

Site-specific Variable Rate Irrigation (VRI) is a system where a center pivot irrigation system is equipped with the capacity to actuate valves for groups of sprinklers, or to regulate its speed during operation. A control system is used to open and close the valves at various rates (or change the speed) based on the position of the pivot and a desired application depth. VRI systems have been described in detail by (Evans et al., 2012), (Evans and King, 2010), and (Sadler et al., 2005). One aspect of VRI that has not been studied is the potential for mitigating some of the undesirable effects of deficit irrigation. When deficits are imposed on a field they are generally estimated based on an average for the whole field. Because no field is completely uniform, some areas of the field will experience more stress than the targeted amount. This can produce visible areas of crop stress even though the overall yield response is still optimal. By using the VRI system, it may be possible to produce increased uniformity of yield response and improve the qualitative effect of visibly stressed areas in a field.

One requirement for performing deficit irrigation is that the depth of application may need to change given the timing of a particular irrigation event. For VRI this means that different prescriptions will be required for each irrigation event. Typical practice for VRI is to produce a single prescription that is calibrated to physical or chemical attributes of the soil and use this prescription repeatedly during the season. In this demonstration the prescriptions are based in the soil moisture status at the time of the irrigation event. The difference between prescriptions will likely be small in most cases but will be significant enough in certain cases to warrant generation of unique prescriptions.

Demonstration Project

The demonstration project began in the spring of 2012 and is planned to be a multi-year effort. Three farms in the Columbia Basin agreed to participate in the demonstration. These farms were selected on the following bases: 1) high lift requirements for pumping (to ensure significant energy costs); 2) farm/irrigation managers willing to experiment with new technologies; 3) irrigation managers willing to act on the irrigation recommendation provided by the integrated system; and 4) greater than 500 acres in production. Each farm received the full complement of instrumentation, monitoring, and analysis described below effectively producing three replications of the demonstration. A summary of the fields used during the 2012 and 2013 seasons are shown in Table 1 and Table 2 respectively.

The following technologies were used at each farm:

Variable Rate Irrigation: At each site, one pivot was retrofitted with a variable rate irrigation system with zone control. Systems from two manufacturers were used. Two sites had systems from Valley Inc., and one site had systems from Lindsay Inc.

Soil Mapping: High-resolution soil maps were produced using the methods described by (Fulton et al., 2011). The soils data was used to produce data layers for several soil properties including holding capacity, field capacity.

Flow Monitor: Ultrasonic flow meters (GE Panametrics) were installed on the pivots equipped with VRI. Water use records for the other fields were derived from records kept by the software used to actuate the pivots.

Weather Monitoring: Each farm was equipped with a primary weather station with the sensors required to calculate reference ET. Additionally, each field had a secondary weather station placed well within the field boundary. This secondary weather station was equipped with temperature and relative humidity sensors and radio communication ET calculations were performed using the ASCE Standard equation (Allen, 2005). Two sites had weather stations produced by Automata Inc. and two sites had weather stations produced by Ranch Systems Inc.

Soil Moisture Monitoring: Each field was equipped with three soil moisture monitoring sites. At each site a neutron probe tube was installed. Additionally two of the sites had Decagon 10HS capacitance probes installed at three depths and one site a multi sensor AquaCheck probe. In each of the fields, the sites were chosen such that they represented the upper, lower, and middle quantiles of holding capacity

Localized Yield Modeling: At each site, a local calibration of the FAO33 yield reduction model was produced using historical yield records. This calibration will enable generations of more precise yield maps and enable consideration of the value of these maps relative to default or regionally estimated yield calibrations.

Yield Mapping: Harvest monitors with GPS tracking will be collected at each site. At two sites a John Deere Green Star 3 monitor was used and at one site a Case IH Pro 600 monitor was used.

To facilitate comparison of various combinations of technologies, the fields grouped into three different levels of integration. Each level represents a significant improvement in scheduling precision and potential for water and energy savings relative to the previous level. Level 1 is the equivalent to basic Scientific Irrigation Scheduling (SIS) where a water balance is used to drive irrigation scheduling. However, this capacity is enhanced by utilizing in-field temperature and relative humidity sensing to refine ET estimation, and neutron probe measurements to correct the water balance. Level 2 builds on Level 1 by adding additional soil moisture monitoring and high resolution soil maps. The soil maps enable explicit consideration of spatial variability which will lead to more accurate yield estimates and more robust management capacity. The additional soil moisture monitoring enables increased temporal resolution and the opportunity to assess data integration issues with different sensors, data loggers, and telemetry. Level 3, the final level, adds VRI capacity.

Table 1 Field designations for 2012 field demonstrations.

Field Number	Integration Level	Crop (2012)	Size (Ac.)	Pumping Lift (ft.)	Location
18	Level 3	Winter wheat	69	≈750	OR
11	Level 2	Winter wheat	82		
17	Level 1	Alfalfa (mature)	125.3		
25		Potatoes	119.2		
102	Level 3	Alfalfa	125	≈750	WA
107	Level 2	Alfalfa	72		
109	Level 1	Alfalfa	125		
210		Alfalfa	125		
2	Level 3	Winter wheat	136	≈125	ID
1	Level 2	Winter wheat	155		
3	Level 1	Sugar beet	147		
6		Sugar beet	134		

Table 2 Field designations for 2013 field demonstrations.

Field Number	Integration Level	Crop (2013)	Size (Ac.)	Pumping Lift (ft.)	Location
M13	Level 1	Canola	124	≈750	OR
M22	Level 2	Canola	132		
M21	Level 3	Canola	121		
M10	Level 1	Field Corn	126	≈750	OR
M56	Level 2	Field Corn	123		
M54	Level 3	Field Corn	123		
B211	Level 1	Field Corn	97	≈750	WA
B116	Level 2	Field Corn	125		
B207	Level 3	Field Corn	102		
TD5	Level 1	Field Corn	125	≈125	ID
TD11	Level 2	Field Corn	125		
TD7	Level 3	Field Corn	125		

Results from 2013

At the time of this writing the demonstration program is still ongoing and yield data for all fields from the 2013 season is not yet available. In lieu of full analysis, here we present some preliminary results and a discussion of the issues and complications that occurred during the 2013 season. Several of these issues are likely to have serious implications for further application of SIS on VRI irrigation systems.

System Calibration

During the 2013 season, IMO was used to generate irrigation schedules for all of the Level 2 & 3 fields. Water use and neutron probe measurements were also tracked in IMO for the Level 1 fields. Simulation of soil moisture for each 12 demonstration fields is shown in the figures below. Overall the system calibrations were satisfactory. The calibrations will be used on the same fields in 2014 and will enable starting the next season with a well calibrated data set for each field.

There were two consistent problems during the season. The first is related to the soil mapping problems described later. The black squares in the graphs represent neutron probe measurements. Three measurements are taken on the same day each week. The measurement sites were selected so that they represented the 25th, 50th, and 70th percentiles of soil water holding capacity. During the season it became apparent that some of the sites did not correspond to those percentiles and were moved to more appropriate sites. The soil mapping issues are described further in the following section.

The second problem was related to the crop coefficients used for field corn. There were several periods where the crop water use (as observed by neutron probe measurements) was significantly less than what the crop coefficient indicated. There were no indications of disease, pest damage, or fertility issues that would have caused the reduction in crop ET. The consequence of this problem is the soil moisture estimates are lower than actual during the peak ET part of the season. This issue is still being explored at the time of this writing.

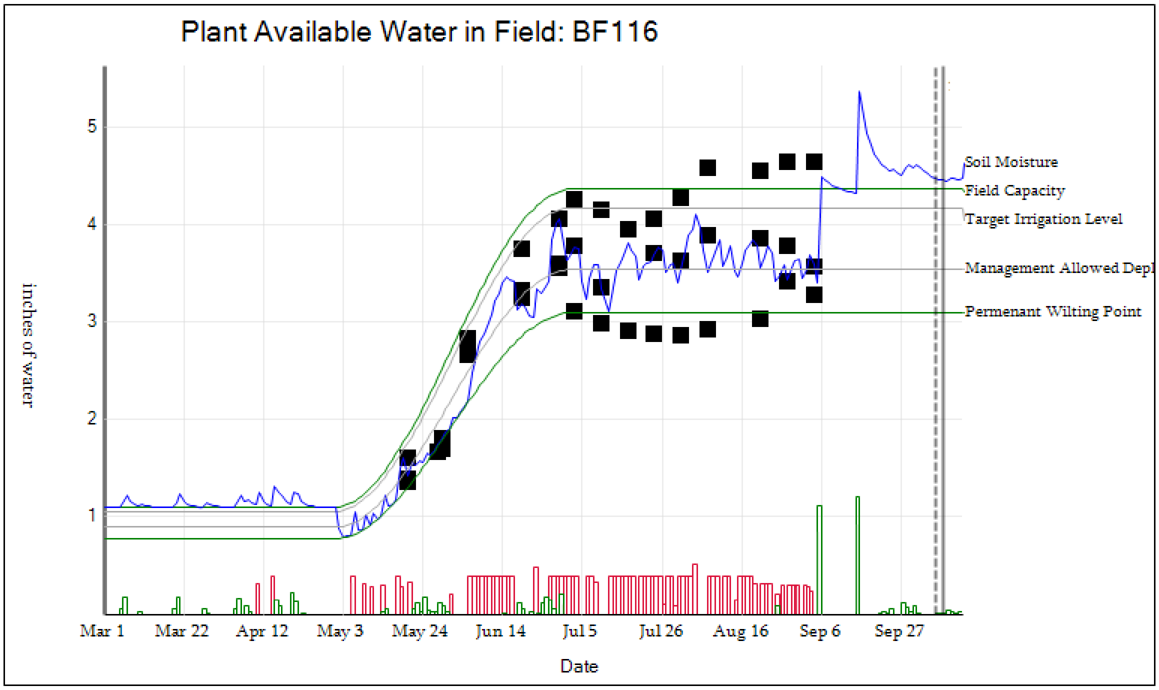

Figure 3 Soil Moisture Estimate for Field BF116

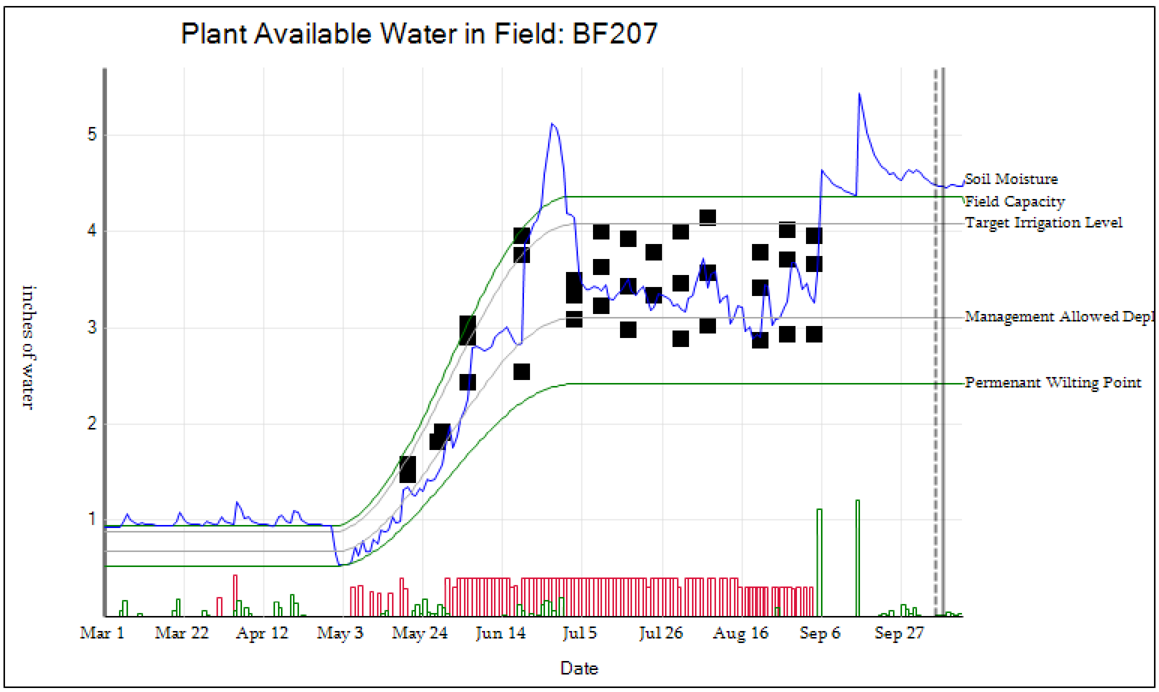

Figure 4 Soil Moisture Estimate for Field BF207

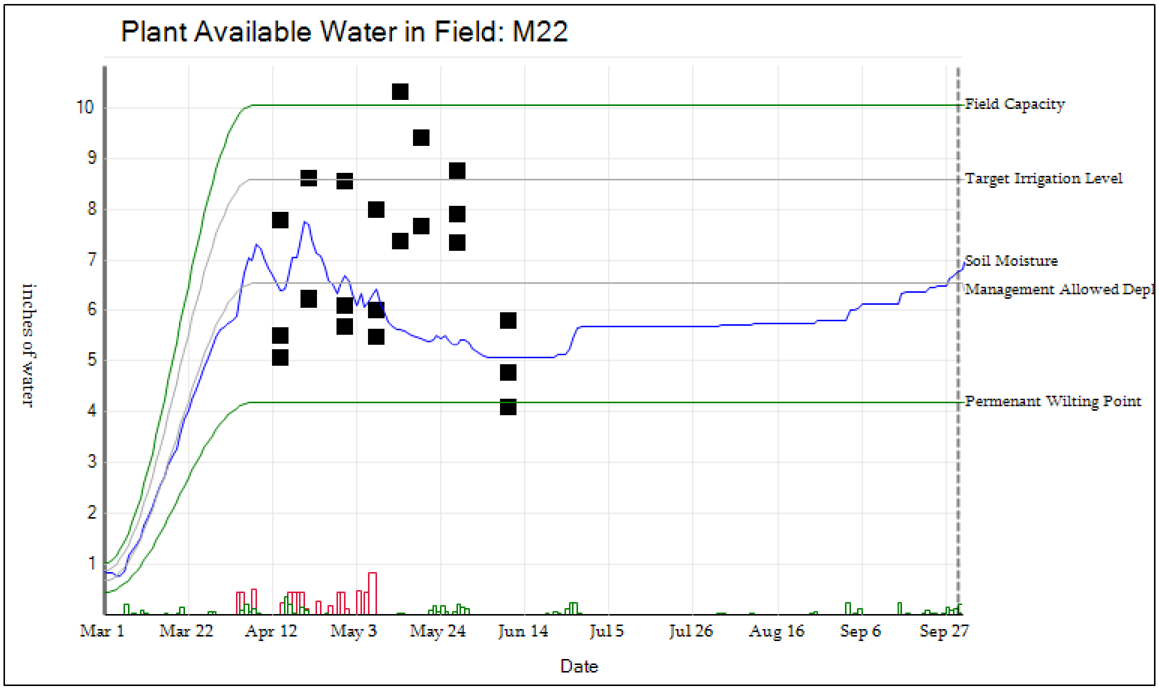

Figure 5 Soil Moisture Estimate for Field M22

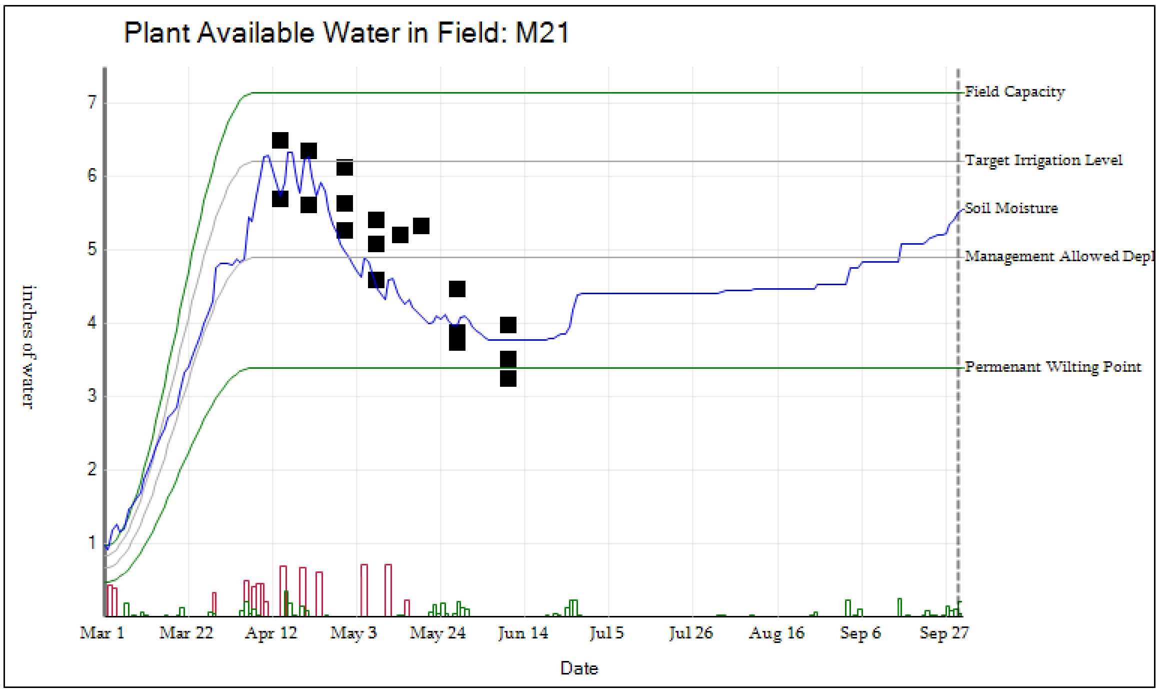

Figure 6 Soil Moisture Estimate for Field M21

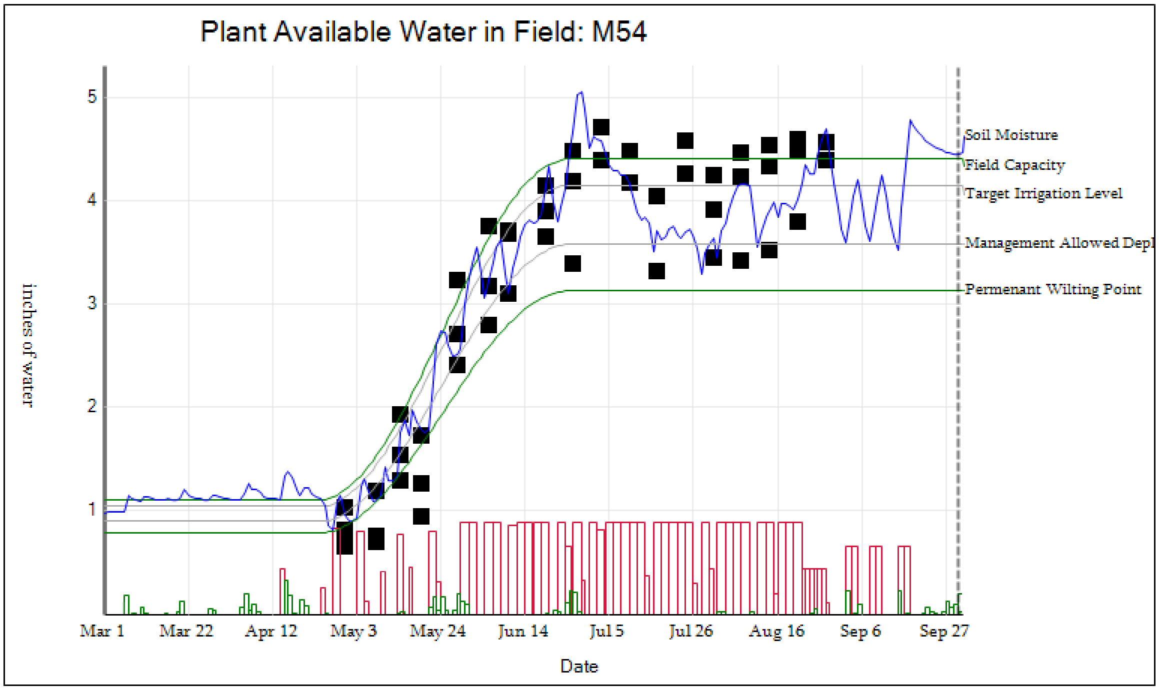

Figure 7 Soil Moisture Estimate for Field M54

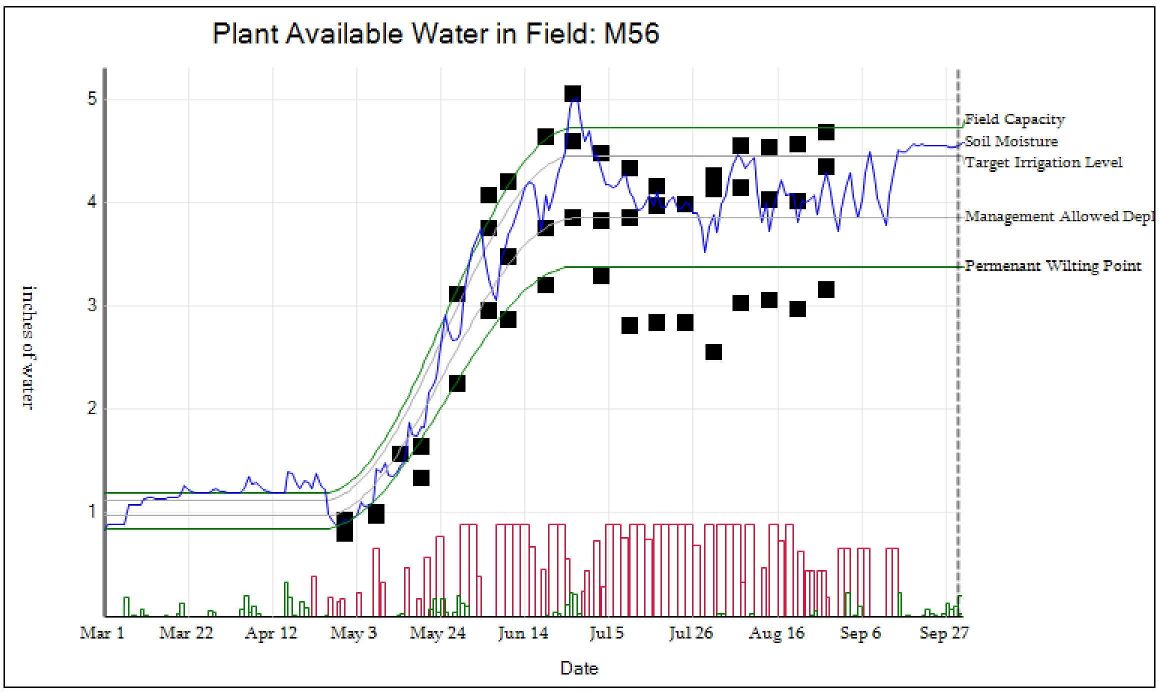

Figure 8 Soil Moisture Estimate for Field M56

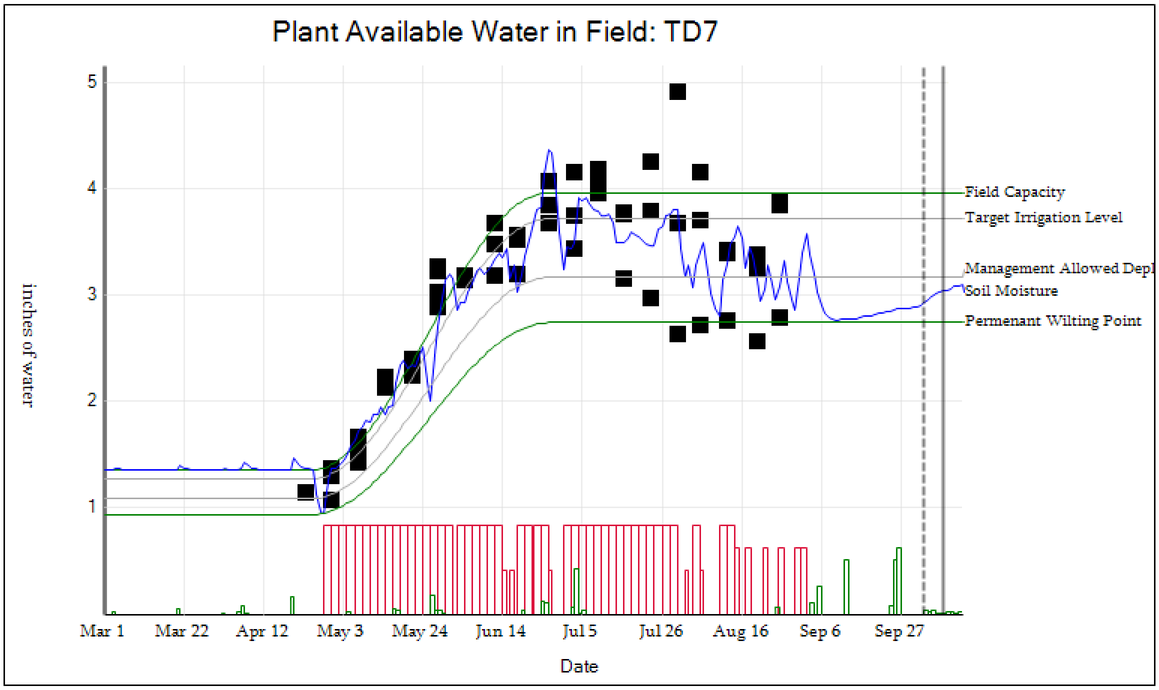

Figure 9 Soil Moisture Estimate for Field TD7

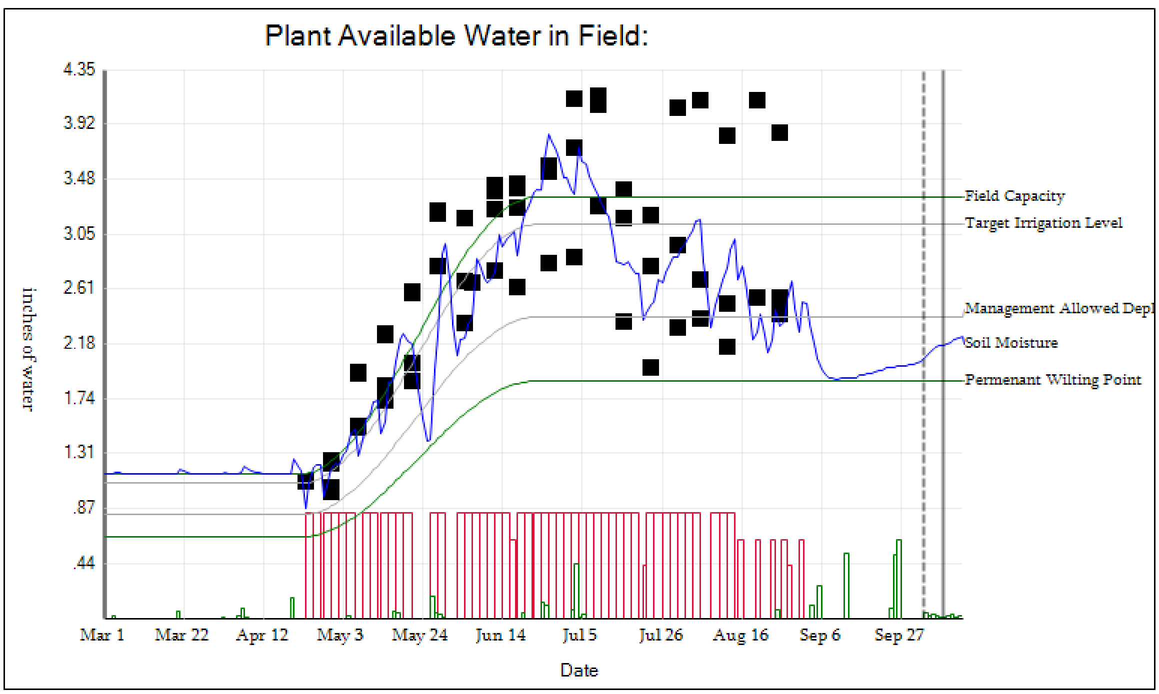

Figure 10 Soil Moisture Estimate for Field TD11

Soil mapping

Scientific irrigation scheduling (SIS) requires the irrigator to know the soil's water holding capacity. To apply SIS with prescribed spatial variation (aka a prescription), the irrigator must have a map of water holding capacity. The methods described in (Fulton et al., 2011) were used to generate a map of field capacity and plant available water. The maps used spatial data from EM38 and Veris systems and soil texture analyses sampled shortly after the EM maps were acquired.

Figure 12 shows the map of surface layer EM readings for one of the Washington site's fields. Figure 13 shows the correlation between the measured soil texture and the modeled texture using the EM maps and a multi-model regression of surface EM, subsurface EM, and soil moisture content. Veracity of the maps was evaluated by correlation between observed soil texture and EC_a, cross validation using the estimated texture and observed texture at the soil sample points, and a qualitative evaluation by the grower. In several of the fields the cross validation indicated very poor correlation between observed EC and texture. The grower's evaluation of the soil maps further confirmed that the generated maps were not representative of observed conditions.

Initial analyses indicated that a potential cause of the poor correlation was recent tillage operations. A group of the fields were remapped first by a different contractor and then again by the first contractor. The resulting maps and cross validations are shown in figures 18 – 21. In several of the maps, correlations improved but not to degree that was fully acceptable.

The exact reason for the map's poor quality is still being examined. Some of the potential issues are:

- Sampling design correlated to tillage practices
- Frozen lens below surface (may cause order of magnitude difference in EC readings)
- Formation of Silica layer (Becomes primary conductance pathway)
- Paramagnetic soil components (Needle formation from freezing may exacerbate EM readings)
- Micro topography effects (Furrows produce periodic effect)

The soil mapping issues have significant implications for further application of SIS with VRI. If reliable maps of PAW cannot be obtained then VRI's application is limited to spatially static prescriptions per field. An additional issue is the cost of the mapping procedure. Complete mapping and analysis cost several thousand dollars. If an accurate map cannot be determined then the field must be remapped, thus incurring further costs. While an accurate map will be valid for several years, a map is also required to evaluate if VRI is appropriate at a given site. The mapping cost and uncertainty of successful mapping are both issues that will need to be addressed.

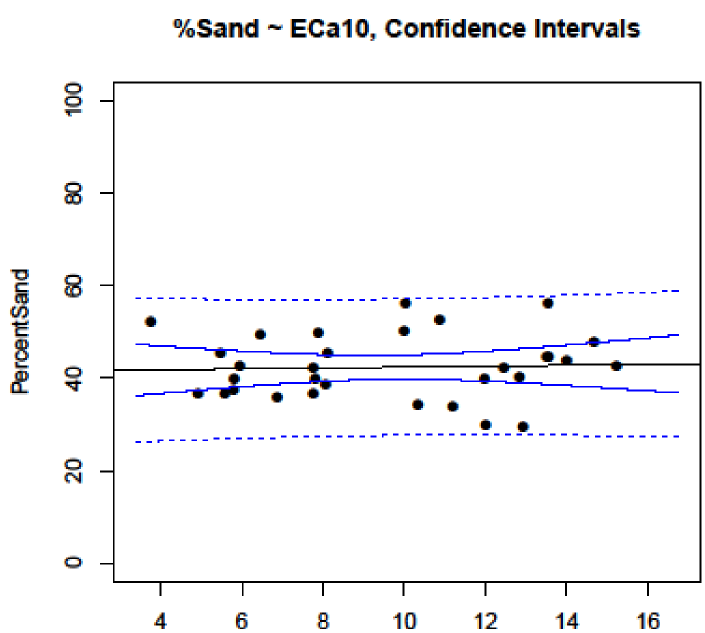

Figure 11 Example of correlation between observed 1m EM reading and measured soil texture. Nearly all the fields at the Washington site had similar levels of correlation.

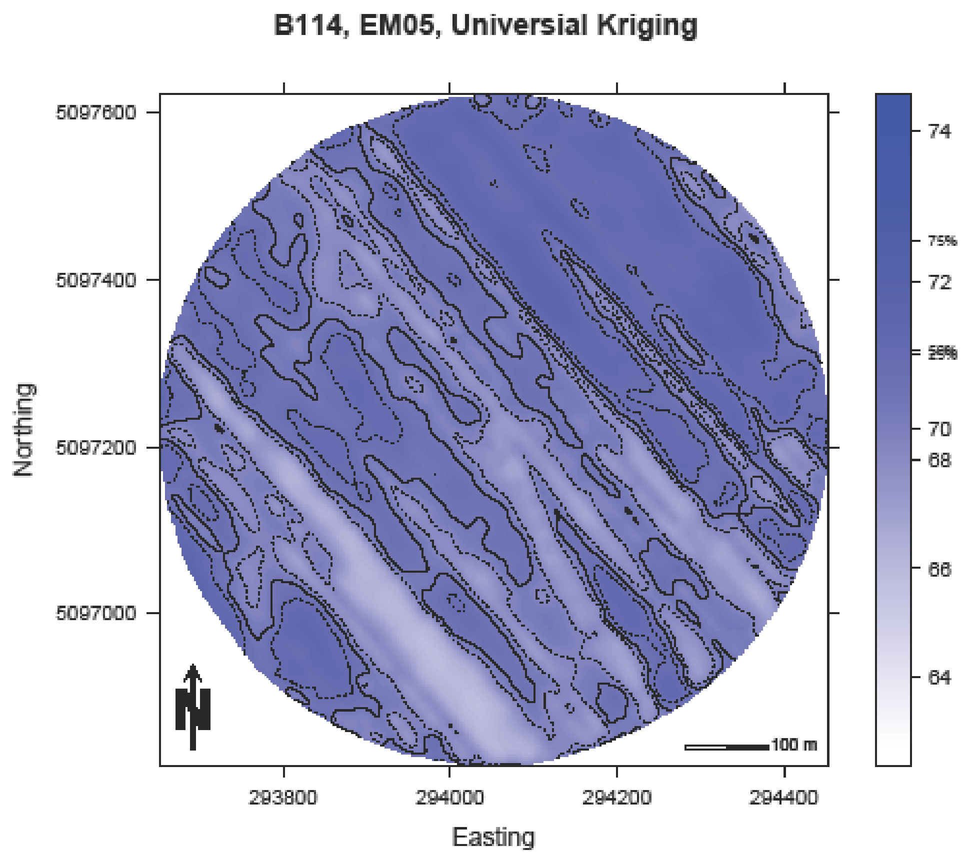

Figure 12 First map of 0.5 meter EM reading on field BF114

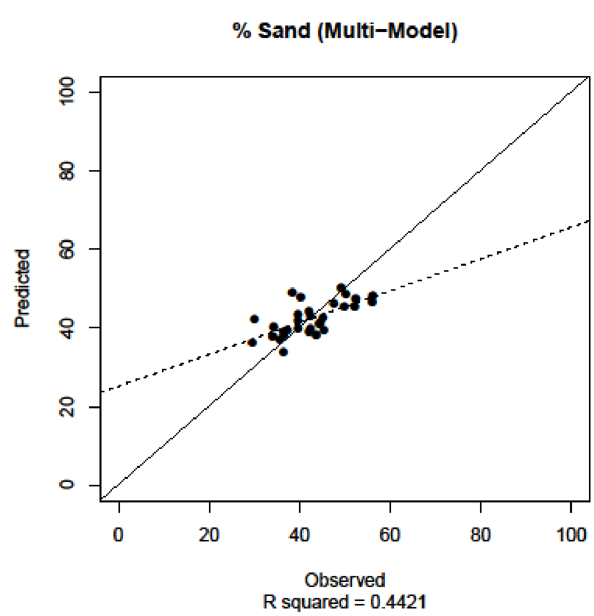

Figure 13 Expected and Observed %Sand derived from first mapping of field BF114. The dashed line is the best fit between observed and predicted.

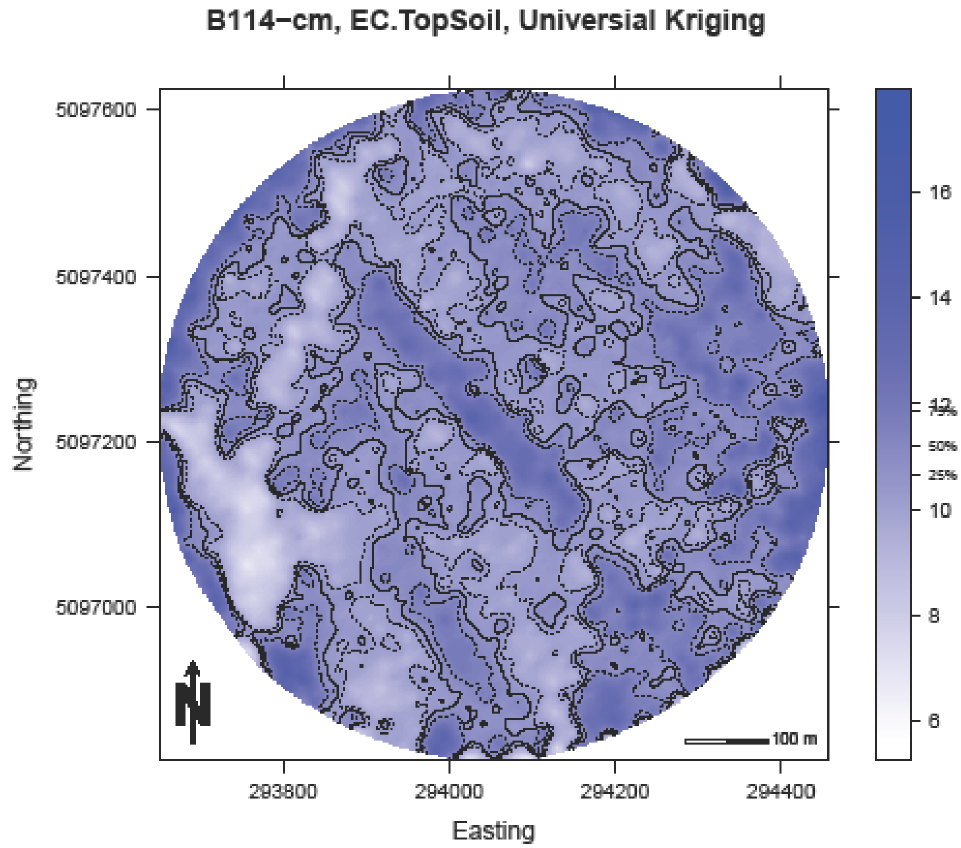

Figure 14 Map of 0.5 m EM readings from second mapping

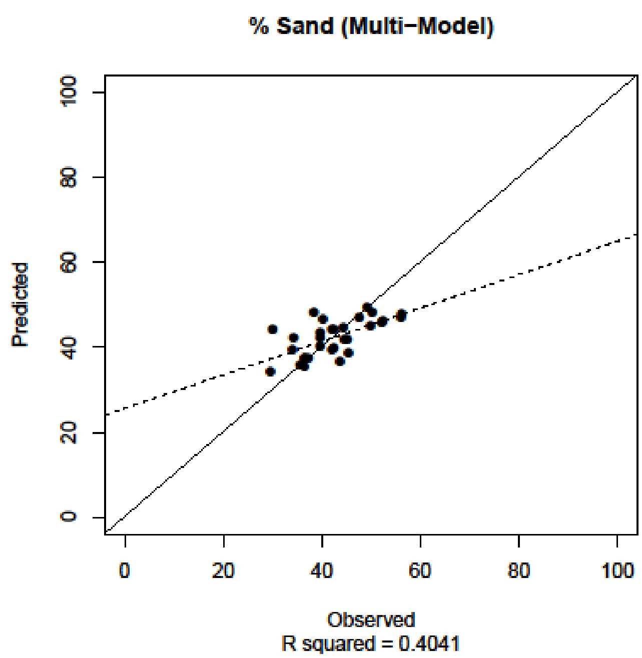

Figure 15 Expected and Observed %Sand derived from the second mapping of BF114

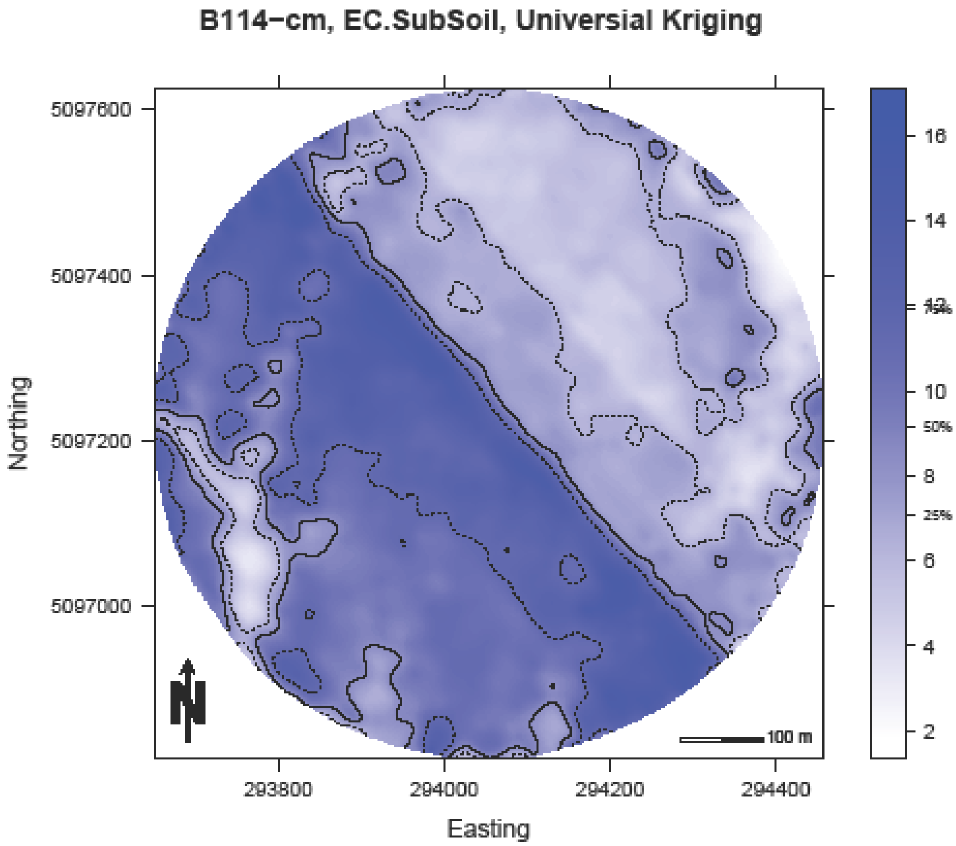

Figure 16 Map 0.5m EM readings from third mapping

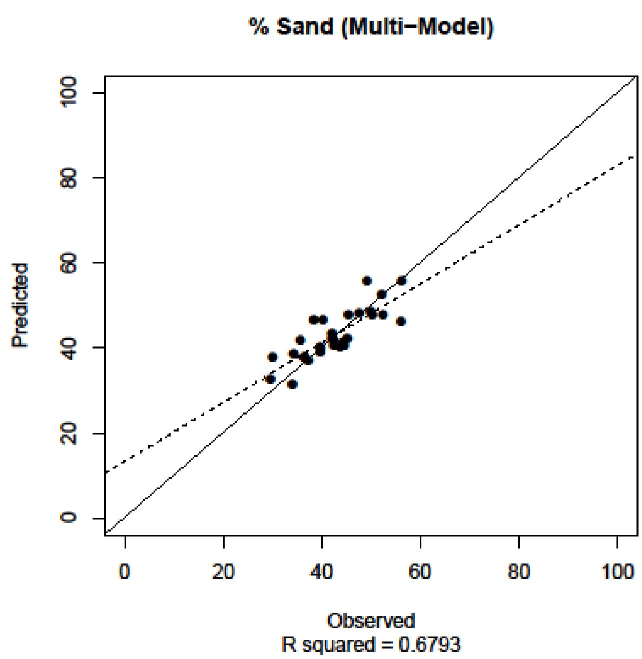

Figure 17 Expected and Observed %Sand derived from third mapping of BF114

M21 Corn Trail

At the beginning of the 2013 season one of the participating growers had an opportunity to participate in a seed corn trial that required planting several small plots spaced far enough apart to satisfy trial requirements. The trial presented a unique opportunity to employ the VRI to combine one of the fields of Canola (M21) and the corn trail. Without the VRI system the grower would have been required to either over irrigate the Canola crop or plow under large sections of the Canola. By using VRI, the corn could be irrigated entirely separate from the canola and only the test plots were replanted. The plot layout and canola yield map are shown in Figure 18 and Figure 19 respectively.

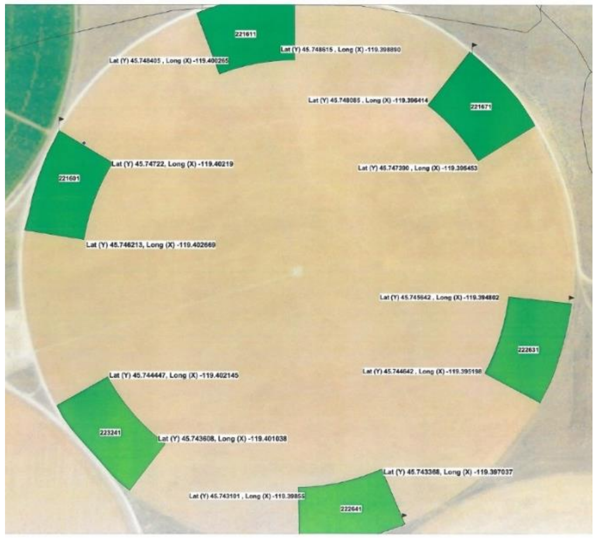

Figure 18 Planting plan for corn trails in existing canola field

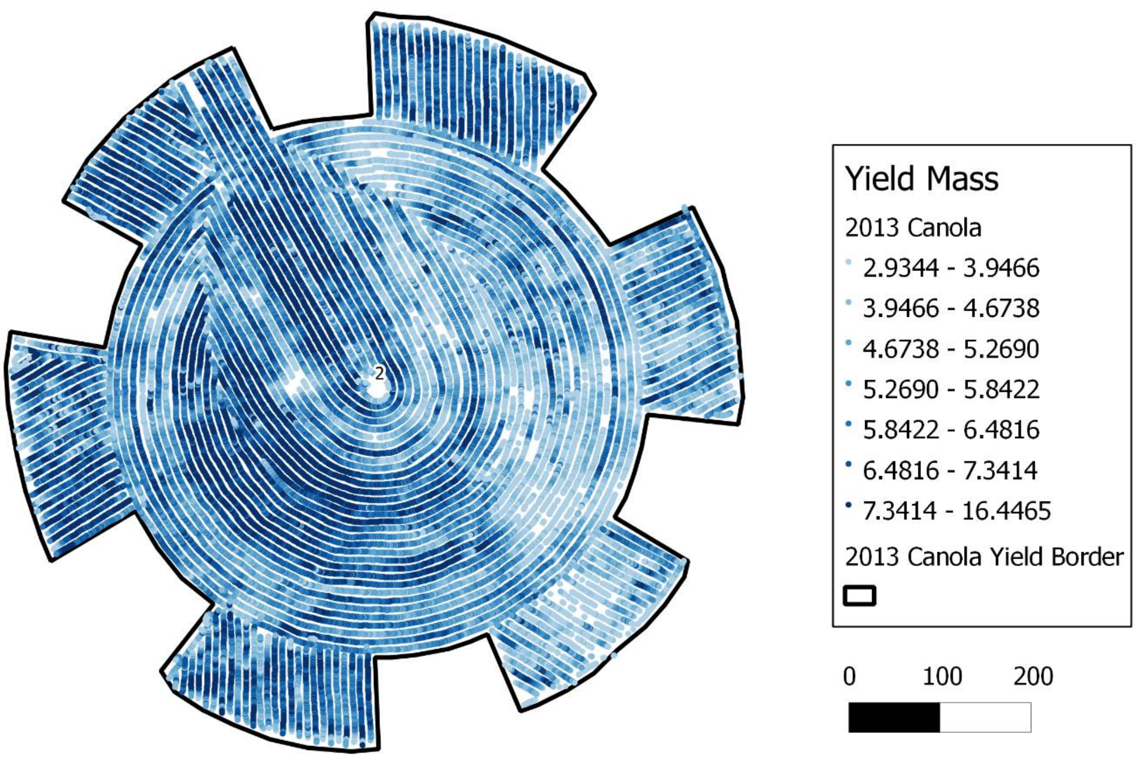

Figure 19 Canola yield map. Missing portions correspond to areas where corn trials were planted

Field Station Telemetry problems

Field Corn was planted in all but three of the demonstration fields during the 2013 season. As plant height increased all of the in-field telemetry sites began to have signal strength attenuation. Figure 20 shows signal strength reported from three such sites. To restore communications the sites had to be moved or adjusted several times during the irrigation season. In some cases only the antenna needed to be raised, however many of these moves incurred nontrivial costs from labor. Furthermore, the disruptions produced gaps in the dataset that prohibited reliable calculation of field specific reference ET. Accurate on-farm estimates of reference ET is a significant component of the integrated system. The repeated communication outages effectively reduced the value of the remote telemetry systems by limiting the quantity of data they produced. This issue is crop specific but still has important implications for precision management of irrigation. Without reliable communication the utility of infield instrumentation and telemetry is questionable.

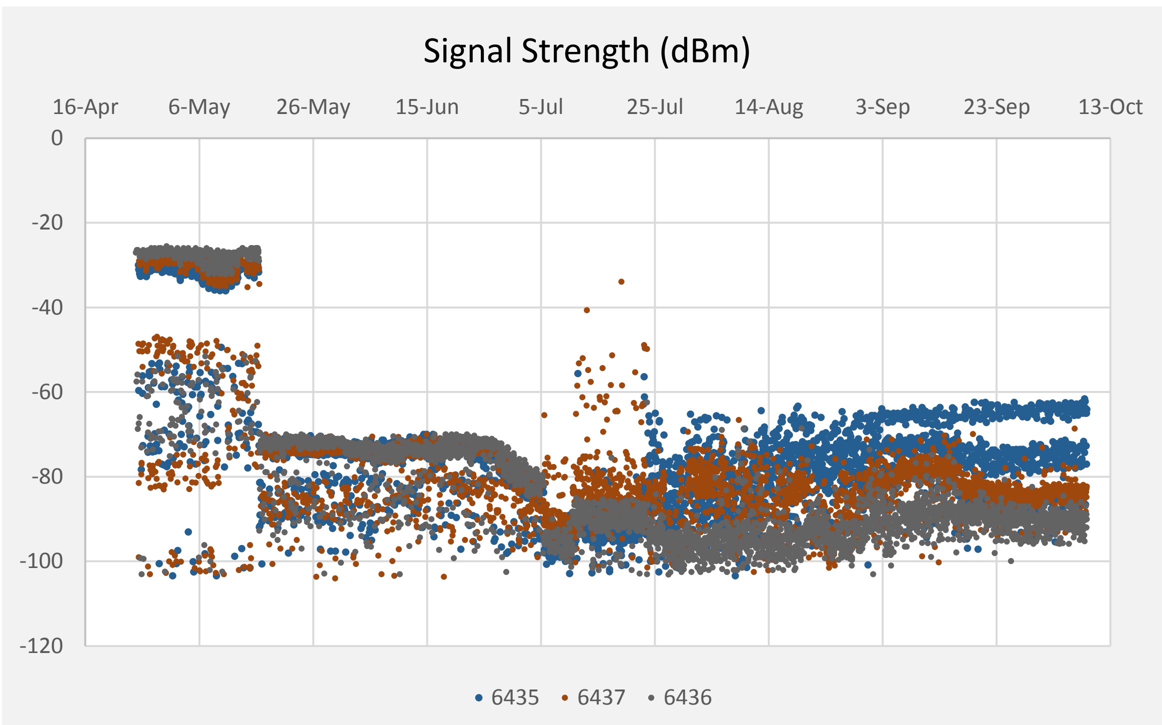

Figure 20 Field station signal strength during 2013 season

VRI telemetry

VRI systems from two different manufacturer were used during the 2013 season. Since frequent revision of the VRI prescriptions is a critical component of the Integrated System, remote upload of prescriptions was needed. One of the manufacturers had a remote upload system however this system was not compatible with the growers existing remote management system. The other manufacturer did not have a remote upload solution (that feature was still under development at the time). For the first manufacturer we were able to obtain remote access to the grower’s office computer where the pivot control systems were installed. Obtaining this access was tentative because one grower has security and safety concerns regarding uncoordinated operation between the experiment team and the farm personnel. This method of access is not considered and effective long term solution. At the second manufacturer’s site a cellular modem was installed to enable remote communication by the experiment team. Finding reliable cellular communication and configuration of the communication was problematic but ultimately successful. This solution was considered acceptable long-term solution provided that reliable cellular communication is available. Both manufactures indicated that in-house solutions will be available in the future.

Conclusion

A demonstration of the economic potential of optimal irrigation and variable rate irrigation was conducted on three farms in the Columbia Basin during the 2012 and 2013 irrigation season. This demonstration employed substantial environmental monitoring, integrated decision support systems, and precision irrigation systems. This demonstration is a multi-year effort and the subsequent years are anticipated to utilize a fully integrated management solution. In 2014, there will be additional cooperating farms across the Northwest testing this and other systems.

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Response of Sunflower to Deficit Irrigation

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Abstract. A study was conducted in 2010-2012 in SW Colorado to quantify the response of sunflower to water deficit. Water was applied pre-plant only (Pre-P), during the growing season (Full), at bud initiation through flowering (R1-6), or during flowering (R4-6). Another treatment was added to mimic irrigation with siderolls (Veg). The Full irrigation treatment outperformed the other treatments in 2010 and 2011 but was similar to R1-6 in 2011. Seed yields of Veg, R4-6 and R1-6 were similar in 2010 while R4-6 ≡ R1-6 in 2011. In 2012, Mycogen 8H449CLDM had greater seed yield than the short stature hybrid Triumph s870HCL, except at Full. The latter is more suitable to irrigation with siderolls, which are prevalent in SW Colorado. Irrigation plus rain closely matched sunflower ET at Full. Season rainfall was greatest in 2010, with 3.3 in. recorded in August. Precipitation use efficiency was generally highest with Pre-P and lowest with Full. In contrast, seed oil content of Full was significantly more than that of the other treatments. The treatment that received little or no irrigation after planting (Pre-P) had the lowest seed oil content in 2010 and especially in 2011. Full irrigation and Veg had the tallest plants while Pre-P and R4-6 had the shortest plants. Applying water mostly during bloom did not affect seed yield or oil content in 2010 and 2011 compared to R1-6. Substantial water conservation and use efficiency can be achieved with limited but targeted irrigation of sunflower.

Keywords. Sunflower, irrigation scheduling, seed yield, oil content, plant height.

Introduction

Contrary to popular belief, sunflower may use as much or more water than other field crops such as corn to produce maximum yield (Meyer at al., 2009). With its deep taproot (Stone, 2002), sunflower can extract water down to 7 or 8 ft., thus reducing the need for additional water from rain or irrigation to meet evapotranspiration (ET).

At Akron, CO, Nelson (2007) derived the following response of sunflower to irrigation:

$$\text{Yield (lb/acre)} = 150.6*(\text{inches water use} - 6.9)$$

Seed production started at 6.9 in. of water consumption. Each additional inch of water produced approximately 151 lb/acre.

Long-term average precipitation from May through September in Yellow Jacket is 6.7 in. Assuming 6.0 in. of effective rainfall during the growing season and 4.0 in. of available soil moisture at planting, it would take an additional 2.2 in. of water to produce 800 lb/acre of sunflower seeds, which was about the average dryland yield in SW Colorado in 2006-2008. It would take another 5.3 in. to double the yield.

Sunflower is most sensitive to water stress "just before flowering through seed development" (Meyer et al., 2009). Schneekloth (2007) achieved 60% water saving compared to full irrigation when he applied water at the R-4 to R-5 stage. Seed and oil yields were equal or higher to those obtained with full irrigation in two (2003 and 2005) out of the four-year period (2002-2005) of the study. There was plenty soil moisture (field capacity in 0- to 6-ft) at planting in 2002 and 2003. When there was less water available at planting or during the growing season, full irrigation outperformed the limited irrigation treatments. Withholding irrigation until R-6 to R-7 increased oil concentration significantly compared to full irrigation. Conversely, applying water at R-1 to R-3 (bud stage) *only* reduced seed oil concentration. Seed yield was similar to that of when irrigation was withheld until R-6 to R-7.

The area where this study was conducted is within the Dolores Irrigation Project, which provides irrigation water to approximately 62,000 acres of crop land in Dolores and Montezuma counties. Pressurized water of excellent quality is delivered to each farm in the full service area (FSA) of the project. Each farmer is allocated close to 2.0 acre feet of water per season. The total FSA annual water allocation was reached or exceeded several times since irrigation began in 1987. Reasons for this include frequent droughts and the predominance of alfalfa (> 80% of the irrigated acreage), which is a high water user. Wheel-line sprinkler systems (siderolls) prevail in the FSA. The price FSA irrigators pay for water has been on the rise due to increases in pumping and maintenance costs. Thus conserving water and enhancing its efficiency is important to the long-term sustainability of the FSA.

Alfalfa ground is usually planted to dry bean, oat or spring wheat for one to two years before reseeding it to alfalfa. Sunflower would be a good crop to plant after alfalfa e.g., to mine the residual water and nitrogen that may be available beyond the reach of dry bean or spring cereals. Moreover, it appears that sunflower responds well to deficit irrigation.

The main objective of this study was to determine the response of sunflower to irrigation deficit.

Materials and Methods

A field trial was conducted at the Southwestern Colorado Research Center in Yellow Jacket, CO in 2010, 2011, and 2012. The soil at the study site is Wetherill loam (fine-silty, mixed, superactive, mesic Aridic Haplustalfs). Normal annual precipitation is 15.9 in., with June being the driest month (0.5 in.), and Aug., Sept., and Oct. the wettest months (1.7 to 1.9 in.). The elevation at the site is 6900 ft. Approximately 40% of the annual precipitation comes from snow.

Sunflower planting dates and irrigation scheduling are shown in Tables 1 and 2, respectively. Sunflower was planted in 30-in rows with a 4-row Monosem NG Vacuum Planter. Row length varied from 50 to 100 ft. The two middle rows were harvested in full or partially for yield estimates. There were four replications in 2010 and 2011 and three in 2012.

Table 1. Sunflower planting dates and rates

	2010	2011	2012	
Sunflower hybrid	Mycogen 8H449CLDM	Mycogen 8H449CLDM	Mycogen 8H449CLDM	Triumph s870HCL
Planting date	4-Jun	1-Jun	1-Jun	1-Jun
Planting rate (seeds/acre)	15,488 & 22,082	22,082	25,344	25,344
Harvest date	11-Nov	Oct. 17-20	Oct. 31 & Nov. 1	

Table 2. Irrigation treatments and amounts

Irrigation treatment	Description	Net post-planting irrigation depth (in.)[1]		
		2010	2011[2]	2012
Pre-P	Pre-plant irrigation (PPI) only	0.0	2.5	0.0
Full	PPI + Full-season irrigation[3]	11.4	18.1	16.2
R1-6	PPI+ Irrigation at R-1 to R-6[3]	3.1	11.7	8.7
R4-6	PPI + Irrigation at R-4 to R-6[3]	2.6	7.2	4.5
Veg	PPI + Sideroll Irrigation[4]	6.6	4.9	NA
PPI (with sideroll)		1.8	0.8	2.5
Rainfall		7.1	4.2	4.4
Full irrigation treatment crop ET		19.8	21.9	20.5

[1] Depth of irrigation after planting. Post-planting water was applied with subsurface drip irrigation (SDI) at approximately 90% efficiency.

[2] Two irrigations were applied early in the season to all the treatments to enhance seed germination and seedling emergence.

[3] Irrigation to meet crop ET during the designated treatment period. R-1: The terminal bud forms a miniature floral head, R-4: The inflorescence begins to open, R-6: Flowering is complete.

[4] Treatment to mimic irrigation with sideroll. Irrigation is terminated when sunflower interferes with the movement of the sideroll, which usually occurs at R-1 for standard-height sunflower.

Results and Discussion

2010

Irrigation scheduling had a significant impact on seed yield, oil yield, and plant height. The full irrigation treatment (Full) produced the highest seed yield of approximately 3000 lb/acre while pre-plant irrigation only (Pre-P) produced the lowest yield of 2334 lb/acre (Fig. 1). Treatments R1-6 and R4-6 received a total of 3.1 and 2.6 in. of net irrigation amount (in addition to pre-plant irrigation), respectively, which is about half the amount (6.6 in) received by Veg and yet, all three treatments had similar yields of approximately 2600 lb/acre. The sideroll-alike treatment (Veg) received most of the irrigation water during the mid-vegetative to early reproductive growth stages or until sunflower plants were too tall to irrigate with the sideroll.

In general, sunflower production in 2010 was enhanced by good water availability at planting and timely and above average rainfall during the reproductive growth stages. Precipitation use efficiency (lb of seeds/in. of rain plus irrigation) was highest at Pre-P and lowest at Full and Veg (Fig. 1). R4-6 and R1-6 had similar precipitation use efficiencies of around 280 lb/in.

The Full treatment had the highest seed oil content, significantly more than the other irrigation treatments, although the range in seed oil content values (39.9 to 41.3%) was small (Fig. 5). The Full and Veg treatments had the tallest plants on average, followed by R1-6. Pre-P and R4-6 had similar plant height of 55 in. (Fig. 8).

Increasing seeding rate from 15,488 to 22,082 seeds/acre increased seed yield by only 121 lb/acre on average (Data not shown). A larger increase (454 lb/acre) was observed at R4-6.

2011

Irrigation treatments that received water during reproductive growth (Full, R4-6, and R1-6) outperformed Pre-P and Veg (Fig. 2). The Full irrigation treatment and R1-6 produced around 3100 lb seeds/acre while R4-6 averaged 2878 lb/acre. The pre-plant irrigation treatment had the lowest yield (1854 lb/acre) followed closely by Veg. All the treatments received 2.5 in. of irrigation water shortly after planting due to dry conditions at planting. Precipitation use efficiency was highest with Pre-P and R4-6 and lowest with Full (Fig. 2).

Seed oil content increased in a near linear fashion with increasing irrigation amounts (Fig. 6). The Full irrigation regime averaged 41.3% followed by R1-6 and R4-6. The Pre-P treatment lagged behind with 37.5%. Sunflower plants averaged 45.7 in. in height with Pre-P and R4-6 and 51.4 in. with the other treatments. As in 2010, restricting irrigation mostly to the flowering period (R4-6) reduced plant height but it did not negatively impact seed yield or oil content when compared with R1-6.

2012

Seed yield increased significantly with increasing irrigation amounts (Fig. 3). Mycogen H449CLDM outperformed Triumph s870HCL at all irrigation levels, except at Full. Mycogen H449CLDM had higher precipitation use efficiency (PUE) at Pre-P and R4-6 and similar PUE at R1-6 and Full (Fig. 4).

On average, Full had the highest seed oil content of 43.8%, significantly more than that of R4-6 and R1-6. Treatment Pre-P had the lowest seed oil content of 41.7% (Fig. 7). Mycogen 8H449CLDM and Triumph s870HCL averaged 43.2% and 41.9%, respectively. Plants of both hybrids were tallest at Full followed by R1-6. Treatments R4-6 and Pre-P had similar plant heights (Fig. 10). As would be expect, s870HCL was much shorter than 8H449CLDM.

Conclusion

The full irrigation treatment outperformed the other treatments in 2010 and 2011 but was similar to R1-6 in 2011. Seed yields of Veg, R4-6 and R1-6 were similar in 2010 while R4-6 ≡ R1-6 in 2011, at P=0.05. In 2012, Mycogen 8H449CLDM had greater seed yield than the short stature hybrid Triumph s870HCL, except at Full. Mycogen 8H449CLDM appears to respond better to deficit irrigation than Triumph s870HCL, possibly due to its more extensive root system. The latter is more suitable to irrigation with siderolls, which are prevalent in SW Colorado.

Irrigation plus rain closely matched sunflower ET at Full. Season rainfall was greatest in 2010, with 3.3 in. recorded in August (Fig. 11). Precipitation use efficiency was generally highest with Pre-P and lowest with Full. In contrast, seed oil content of Full was significantly more than that of the other treatments. The treatment that received little or no irrigation after planting (Pre-P) had the lowest seed oil content in 2010 and especially in 2011. The full irrigation and the sideroll-alike (Veg) treatments had the tallest plants while Pre-P and R4-6 had the shortest plants.

Applying water mostly during bloom did not affect seed yield or oil content in 2010 and 2011 compared to R1-6.

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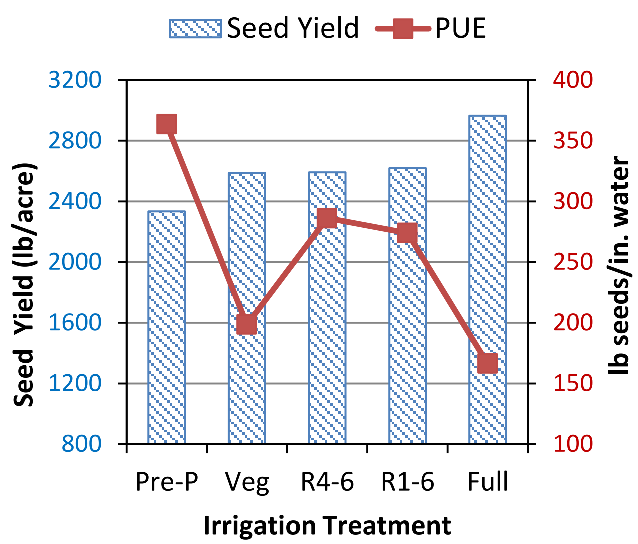

Figure 1. Seed yield and precipitation use efficiency (PUE) in 2010 as affected by irrigation scheduling.

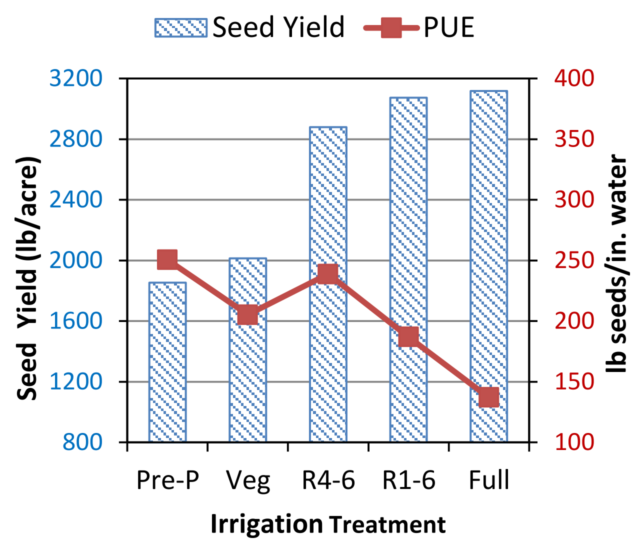

Figure 2. Seed yield and precipitation use efficiency (PUE) in 2011 as affected by irrigation scheduling.

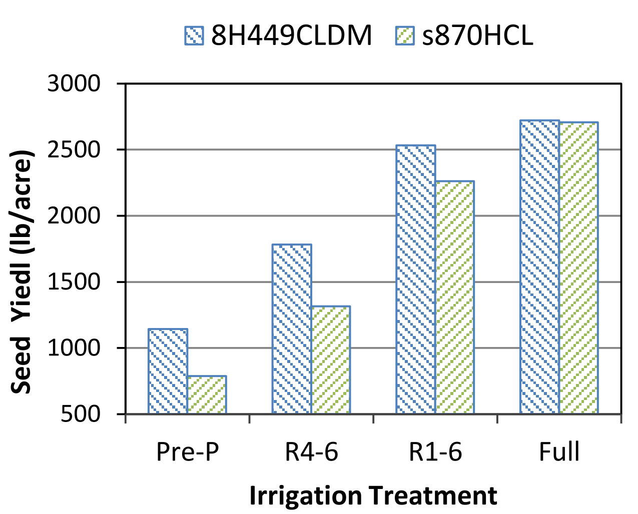

Figure 3. Seed yield of two sunflower hybrids in 2012 as affected by irrigation scheduling.

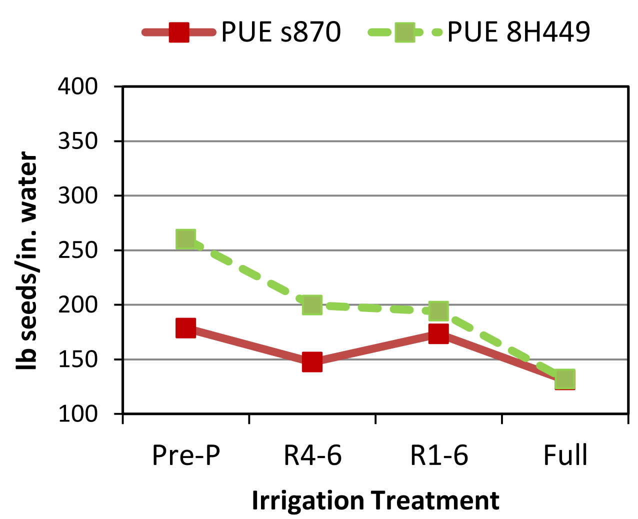

Figure 4. Precipitation use efficiency (PUE) of two sunflower hybrids in 2012 as affected by irrigation scheduling.

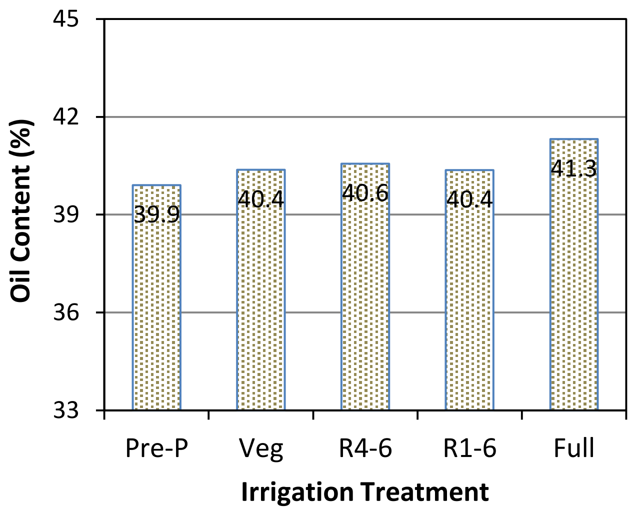

Figure 5. Oil content of sunflower hybrid 8H449CLDM in 2010 as affected by irrigation scheduling.

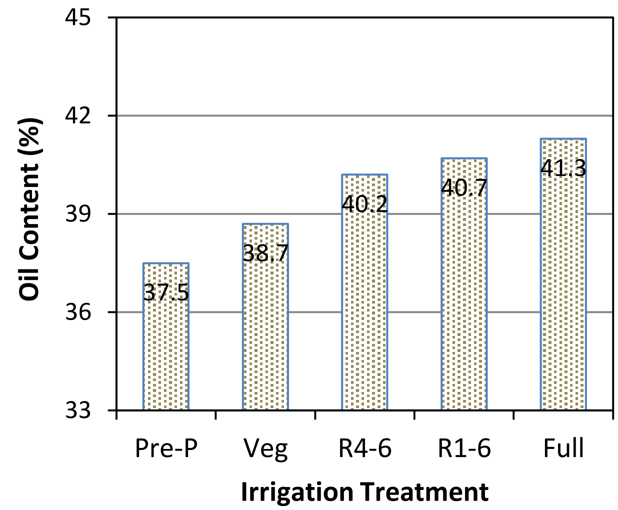

Figure 6. Oil content of sunflower hybrid 8H449CLDM in 2011 as affected by irrigation scheduling.

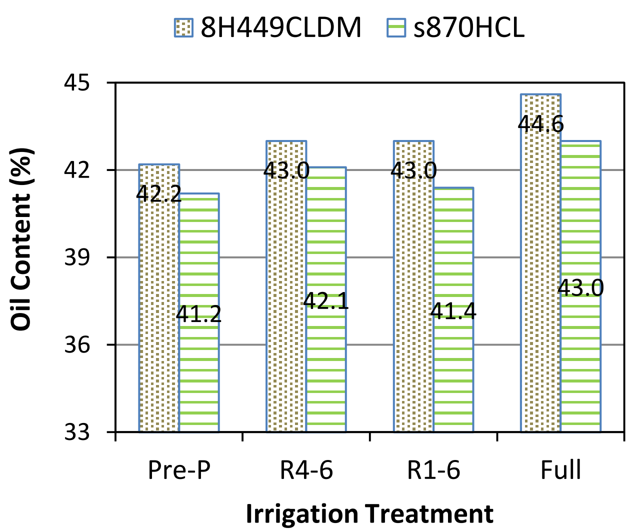

Figure 7. Oil content of two sunflower hybrids in 2012 as affected by irrigation scheduling.

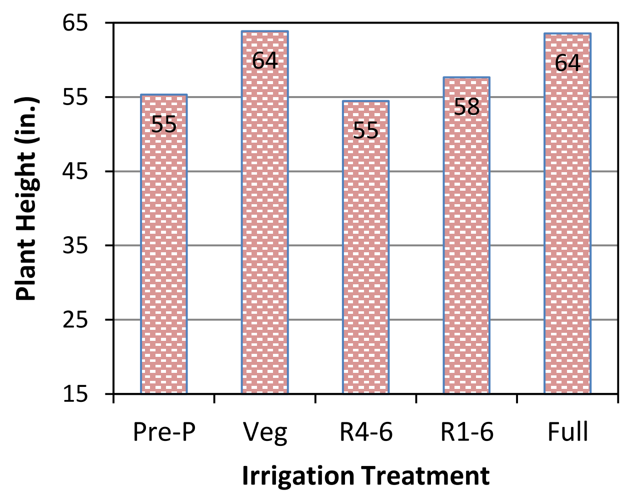

Figure 8. Plant height of sunflower hybrid 8H449CLDM in 2010 as affected by irrigation scheduling.

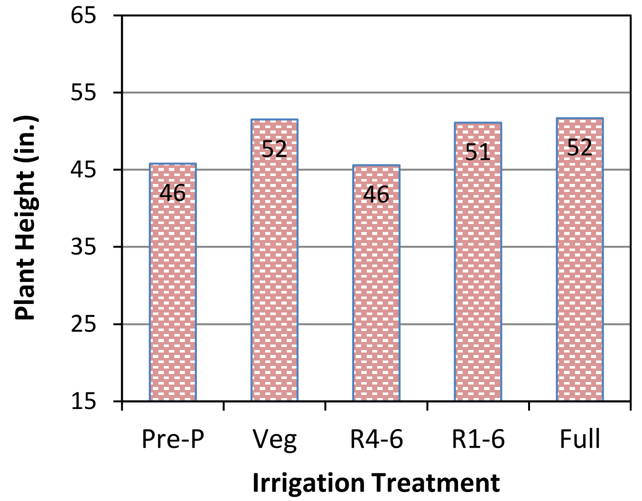

Figure 9. Plant height of sunflower hybrid 8H449CLDM in 2011 as affected by irrigation scheduling.

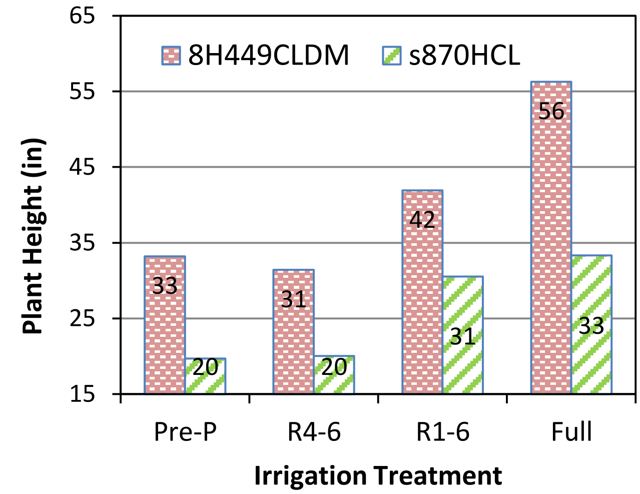

Figure 10. Plant height of two sunflower hybrids in 2012 as affected by irrigation scheduling.

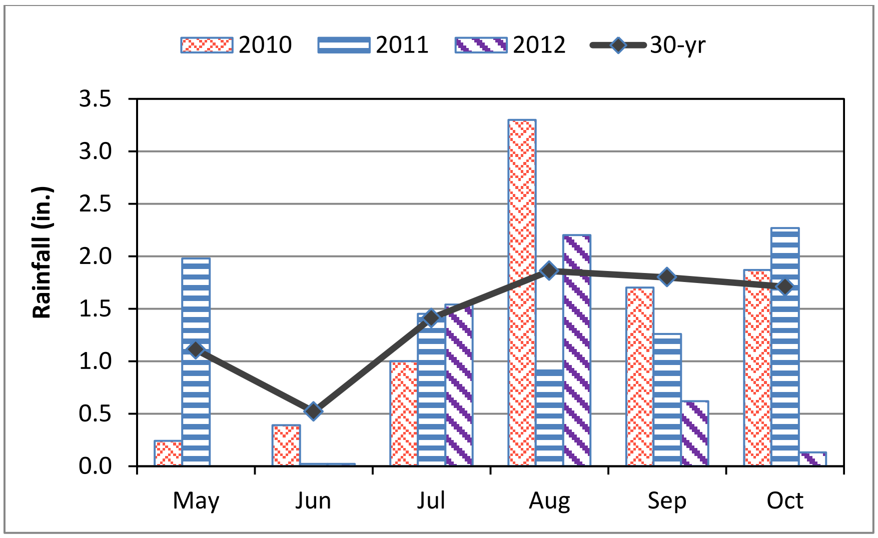

Figure 11. Rainfall in May through September at the study site.

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Irrigation of Sunflowers in Northwestern Kansas

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Abstract. Sunflower was grown in a three year (2009, 2010, and 2012) at the KSU Northwest Research-Extension Center at Colby, Kansas under a lateral move sprinkler irrigation system. Irrigation capacities were limited to not more than 1 inch every 4, 8 or 12 days but were scheduled only as needed as determined with a weather-based water budget. Achene (sunflower seed) yields and oil yield generally plateaued at the medium irrigation level. Dormant season irrigation generally had no appreciable effect on achene yield or other yield components. The optimum harvest plant population for sunflower in this study in terms of achene yield and oil yield was approximately 19,000 to 20,000 plants/acre.

Sunflower and corn have similar peak ET and irrigation rate requirements for full irrigation, but sunflower requires about 2.3 inches less irrigation and its peak needs began at about the time corn needs are starting to decline. Average full irrigation of sunflowers is approximately 12 inches, but often producers will apply between 8 and 10 inches of irrigation because the amount of yield decline is slight.

Keywords. Irrigation scheduling, water budget, sunflower.

Introduction

Sunflower is a crop of interest in the Ogallala Aquifer region because of its shorter growing season and thus lower overall irrigation needs. Sunflowers are thought to better withstand short periods of crop water stress than corn and soybeans and the timing of critical sunflower water needs is also displaced from those of corn and soybeans. Thus, sunflowers might be a good choice for marginal sprinkler systems and for situations where the crop types are split within the center pivot sprinkler land area.

Center pivot sprinkler irrigation (CP), the predominant irrigation method in the Ogallala region, presents unique challenges when used for deficit irrigation. Center pivot sprinkler irrigation cannot be effectively used to apply large amounts of water timed to a critical growth stage as can be done with surface irrigation methods. The CP systems also cannot efficiently use small frequent events to alleviate water stress as is the case with subsurface drip irrigation (SDI). Thus with CP systems, it is important that available soil water in storage be correctly managed temporally in terms of additions and withdrawals so that best crop production can be achieved both economically and water-wise. .

Procedures

The study was conducted from 2009 through 2012 at the KSU Northwest Research-Extension Center at Colby, Kansas under a lateral move sprinkler irrigation system. However, data from 2011 is excluded due to a devastating hail storm that destroyed the crop. Key agronomic characteristics of the annual tests are shown in Table 1.

Table 1. Agronomic characteristics of an irrigated sunflower study conducted at the KSU Northwest Research-Extension Center, Colby, Kansas, 2009-2012. Data from 2011 are excluded due to devastating hail storm.

Characteristic	**2009**	**2010**	**2012**
Hybrid	Triumph S671[1]	Triumph S671	Triumph S671
Planting date	June 18	June 16	June 13
Emergence date	June 25	June 24	June 26
Harvest date	October 16	October 13	October 8
Rainfall, emergence to maturity (inches)	9.89	7.32	5.25
Preseason irrigation (inches)	5	5	9.2
First seasonal irrigation	July 27	July 25	July 25
Last seasonal irrigation	September 15	September 15	September 23

Whole plot treatments were sprinkler irrigation capacities of 1 inch every 4, 8 or 12 days as limited by ET-based water budget irrigation scheduling. An additional whole plot irrigation factor was the addition or no addition of dormant preseason irrigation resulting in a total of 6 different irrigation treatments. The target preseason irrigation amount for those plots receiving it was 5 inches, but in 2012 a total of 9.2 inches of preseason irrigation was applied due to an application error. Three targeted plant populations 18,000, 23,000, or 28,000 plants/acre were superimposed on the whole plots for a grand total of 108 subplots. Irrigation amounts were 1 inch applied as needed, but limited by the imposed capacity and the water budget irrigation schedule. The whole plots (6 reps) were in a randomized complete block (RCB) design.

Soil water was measured periodically in each plot each crop season with a neutron probe to a depth of 8 feet in one foot increments. Crop water use was calculated as the sum of changes in soil water between emergence and physiological maturity, precipitation and irrigation amount. Crop water productivity (WP, also known as water use efficiency) was calculated as the achene yield in lbs/acre divided by the total crop water use in inches.

Sunflower heads were hand harvested from a representative sample area and threshed for yield and yield component determinations.

Results

<u>Weather Conditions</u>

The crop year 2009 was very cool and wet and irrigation needs were low. In-season irrigation amounts for the 1 inch every 4 and 8 days treatments were 7.68, 6.72 and 4.80 inches, respectively. During the period April through October every month had above normal precipitation and between crop emergence and crop maturity the total precipitation was 9.89 inches.

The early portion of the crop year 2010 was wet and irrigation needs were lower than normal. However, later in season, it was extremely dry with only 1.08 inches of precipitation occurring between August 4 and crop maturity on October 11. Precipitation during the sunflower growing period totaled 7.32 inches. In-season irrigation amounts were 11.52, 6.72 and 4.8 inches for the irrigation capacities limited to 1 inch/4 days, 1 inch/8 days and 1 inch/12 days, respectively. The 2010 sunflower irrigation amounts appear to be approximately 1 inch less than normal as estimated from long term (1972-2005) irrigation scheduling simulations conducted at Colby, Kansas.

Extreme drought conditions existed for all of 2012 and only 5.25 inches of precipitation occurred during the sunflower growing period. Additionally, temperatures of 100°F or greater occurred on 20 days between June 26 and August 15. Crop establishment may have been negatively affected by excessively hot temperatures (99 to 104°F) that occurred for the entire period between planting and emergence even though small amounts of irrigation kept sufficient amounts of water in the seed zone. Sunflower plant populations at harvest in 2012 averaged approximately 75% of levels that occurred in 2009 and 2010. In-season irrigation amounts were 13.94, 8.18 and 6.26 inches for the irrigation capacities limited to 1 inch/4 days, 1 inch/8 days and 1 inch/12 days, respectively.

Summarizing the weather conditions, the crop year 2009 was cooler and wetter than normal, the crop year 2010 was approximately normal though a severe drought began in early August, and the crop year 2012 was extremely hot and dry.

Crop Yields and Yield Components

The addition of dormant preseason irrigation did not significantly increase yields in any of the three years (Tables 2, 3 and 4). Preseason irrigation did significantly increase heads/plant in 2009 and harvest plant population in 2010, but these differences were only about 3% greater. There were no significant differences in yield attributable to irrigation capacity in 2009 and 2012, but increased irrigation capacity did increase achene yield in 2010.

There were no plant population effects on achene yield in 2009, but increased plant population decreased achene yield in 2010 and increased achene yield in 2012 (Tables 2, 3 and 4). The difference between 2010 and 2012 responses is probably related to the differences in harvest plant populations between the two years. As indicated in earlier section, crop establishment was poor in 2012. Harvest plant populations in 2010 averaged 19,263, 23,426 and 26,257 plants/acre for the three respective targets as compared to the much lower 2012 values of 14,452, 17,530 and 19,781 plants/acre. Increasing plant population significantly decreased achenes/head in both 2009 and 2010 but had no consistent effect in 2012, once again probably because harvest plant populations were so low (Tables 2, 3 and 4). Increasing plant population significantly decreased achene mass and significantly increased achene oil content (percentage) in all three years. Within a given year average differences in oil content ranged from 1 to 2% as affected by plant population. Harvest plant populations above 19,000 to 20,000 plants/acre resulted in reduced achene yields and oil yields (Figure 1).

Crop Water Use and Water Productivity

In-season crop water use was significantly increased by increased irrigation in all three years (Tables 2, 3 and 4). However, crop water productivity (WP) was significantly reduced by increased irrigation in all three years. Irrigation amounts ranged from 4.80 to 7.68 inches in 2009, 4.80 to 11.52 inches in 2010 and 6.26 to 13.94 inches in 2012. Achene yield and oil yield both increased with irrigation in all years up through the 1 inch/8 day irrigation capacity but tended to have less or no response above that level. Achene yields were lower in 2010 than in 2009 and 2012, but still were towards the upper range of yields for the region.

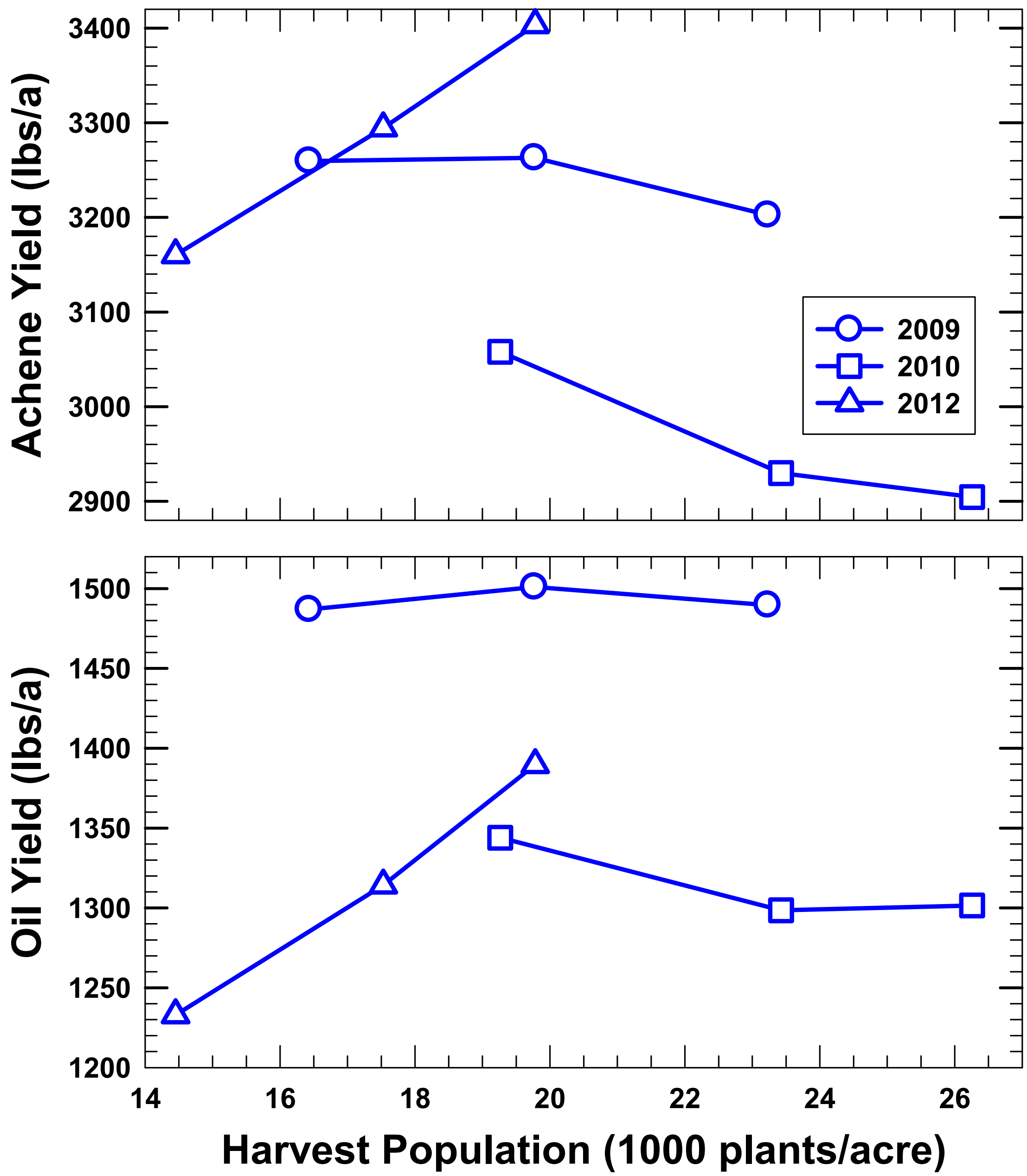

Figure 1. Achene yield and oil yield as related to harvest plant population in a sprinkler irrigated sunflower study, KSU Northwest Research-Extension Center, Colby, Kansas, 2009-2012.

Table 2. Summary of sunflower yield components and water use parameters for a sprinkler irrigated study, 2009, KSU Northwest Research-Extension Center, Colby Kansas.

Irrigation capacity	Preseason irrigation	Targeted plant population (1000 p/a)	Yield (lb/a)	Harvest plant population (p/a)	Heads /plant	Achenes /head	Achene Mass (mg)	Achene Oil%	Water use (inches)	Water Productivity (lb/acre-in)
1 in/4 d (7.68 in)	None	18	3266	16262	0.94	2114	46.6	45.6	21.94	149
		23	3324	20183	0.92	2043	40.2	46.2	22.49	148
		28	3109	23813	0.93	1720	37.2	46.6	22.10	141
		Mean	3233	20086	0.93	1959	41.3	46.2	22.18	146
	5 inches	18	3229	16553	0.94	2155	44.3	45.7	22.06	146
		23	3326	20328	0.93	1919	42.0	46.3	22.24	150
		28	3246	22942	0.99	1728	39.3	46.8	22.96	141
		Mean	3267	19941	0.95	1934	41.9	46.2	22.42	146
Mean 1 inch/4 days			**3250**	**20013**	**0.94**	**1947**	**41.6**	**46.2**	**22.30 c**	**146 b**
1 in/8 d (6.72 in)	None	18	3376	16698	0.95	2259	43.4	45.7	21.08	161
		23	3189	20183	0.95	1893	40.4	46.0	21.29	150
		28	3081	22506	0.96	1790	37.5	46.5	21.89	141
		Mean	3215	19796	0.95	1981	40.4	46.1	21.42	151
	5 inches	18	3427	16553	0.99	2214	42.8	45.0	21.56	159
		23	3208	19312	0.96	1934	40.6	46.1	21.21	151
		28	3332	22506	1.01	1766	38.4	46.6	22.01	152
		Mean	3322	19457	0.99	1971	40.6	45.9	21.60	154
Mean 1 inch/8 days			**3269**	**19626**	**0.97**	**1976**	**40.5**	**46.0**	**21.51 b**	**152 a**
1 in/12 d (4.80in)	None	18	3158	16408	0.93	2198	42.8	45.7	20.38	155
		23	3186	19457	0.96	1923	40.3	45.9	20.75	154
		28	3168	24103	0.91	1728	38.3	46.5	20.75	153
		Mean	3171	19989	0.93	1950	40.5	46.0	20.63	154
	5 inches	18	3100	16117	0.97	2127	42.3	46.1	20.36	152
		23	3345	19166	0.96	1985	41.9	45.6	20.41	164
		28	3279	23522	0.94	1758	38.4	46.2	20.68	159
		Mean	3241	19602	0.96	1957	40.8	45.9	20.48	158
Mean 1 inch/12 days			**3206**	**19796**	**0.95**	**1953**	**40.7**	**46.0**	**20.56 a**	**156 a**
Study-Wide Mean			**3242**	**19812**	**0.95**	**1959**	**40.9**	**46.0**	**21.45**	**151**
Preseason Irrigation	**None**		**3206**	**19957**	**0.94 a**	**1963**	**40.7**	**46.1**	**21.41**	**150**
	5 inches		**3277**	**19667**	**0.97 b**	**1954**	**41.1**	**46.0**	**21.50**	**153**
Target plant population (1000 p/a)		**18**	**3260**	**16432 a**	**0.95**	**2178 a**	**43.7 a**	**45.6 c**	**21.23 a**	**154 a**
		23	**3263**	**19771 b**	**0.95**	**1950 b**	**40.9 b**	**46.0 b**	**21.40 a**	**153 a**
		28	**3203**	**23232 c**	**0.96**	**1748 c**	**38.2 c**	**46.5 a**	**21.73 b**	**148 b**

Shaded items within a column are significantly different at P<0.05 when followed by a different lower-cased letter.

Table 3. Summary of sunflower yield components and water use parameters for a sprinkler irrigated study, 2010, KSU Northwest Research-Extension Center, Colby Kansas.

Irrigation capacity	Preseason irrigation	Targeted plant population (1000 p/a)	Yield (lb/a)	Harvest plant population (p/a)	Heads /plant	Achenes /head	Achene Mass (mg)	Achene Oil%	Water use (inches)	Water Productivity (lb/acre-in)
1 in/4 d (11.52 in)	None	18	3172	20038	0.94	1916	40.4	44.2	22.69	141
		23	2919	23668	0.89	1631	38.6	44.7	22.74	128
		28	2946	27007	0.85	1570	37.4	45.0	23.32	127
		Mean	3012	23571	0.90	1706	38.8	44.6	22.92	132
	5 inches	18	3000	19166	0.93	1845	42.3	43.8	20.99	143
		23	3062	23958	0.95	1646	37.3	44.7	21.15	146
		28	2987	25265	0.95	1597	36.1	45.3	20.72	145
		Mean	3172	20038	0.94	1916	40.4	44.2	22.69	141
Mean 1 inch/4 days			**3014 a**	**23184**	**0.92**	**1701**	**38.7**	**44.6 a**	**21.93 a**	**138 c**
1 in/8 d (6.72 in)	None	18	3043	19602	0.92	1893	41.0	44.5	19.63	157
		23	2989	23377	0.98	1668	36.1	44.6	20.01	150
		28	3004	25700	0.97	1563	35.7	45.3	19.36	156
		Mean	3012	22893	0.96	1708	37.6	44.8	19.66	154
	5 inches	18	3091	18440	0.98	1912	40.6	44.3	19.01	164
		23	2892	23087	0.93	1647	37.2	44.7	19.31	151
		28	2951	25410	0.98	1506	36.3	45.3	19.58	152
		Mean	3043	19602	0.92	1893	41.0	44.5	19.63	157
Mean 1 inch/8 days			**2995 a**	**22603**	**0.96**	**1698**	**37.8**	**44.8 a**	**19.48 b**	**155 b**
1 in/12 d (4.80 in)	None	18	2983	19312	0.96	1868	39.4	43.2	17.25	175
		23	2886	23522	0.96	1715	34.4	43.6	16.85	175
		28	2705	27588	0.88	1480	34.4	44.0	17.10	159
		Mean	2858	23474	0.93	1688	36.1	43.6	17.07	170
	5 inches	18	3059	19021	0.95	1983	39.0	43.7	18.12	170
		23	2831	22942	0.94	1613	37.0	43.6	17.99	158
		28	2833	26572	0.91	1511	35.5	44.1	17.67	162
		Mean	2908	22845	0.93	1702	37.2	43.8	17.93	163
Mean 1 inch/12 days			**2883 b**	**23159**	**0.93**	**1695**	**36.6**	**43.7 b**	**17.50 c**	**167 a**
Study-Wide Mean			**2964**	**22982**	**0.94**	**1698**	**37.7**	**44.4**	**19.64**	**153**
Preseason Irrigation	**None**		**2961**	**23313 a**	**0.93**	**1700**	**37.5**	**44.3**	**19.88**	**152**
	5 inches		**2967**	**22651 b**	**0.95**	**1695**	**37.9**	**44.4**	**19.39**	**155**
Target plant population (1000 p/a)		**18**	**3058 a**	**19263 c**	**0.94**	**1903 a**	**40.5 a**	**43.9 c**	**19.61**	**158 a**
		23	**2930 b**	**23426 b**	**0.94**	**1653 b**	**36.8 b**	**44.3 b**	**19.67**	**151 b**
		28	**2904 b**	**26257 a**	**0.92**	**1538 c**	**35.9 b**	**44.8 a**	**19.62**	**150 b**

Shaded items within a column are significantly different at P<0.05 when followed by a different lower-cased letter.

Table 4. Summary of sunflower yield components and water use parameters for a sprinkler irrigated study, 2012, KSU Northwest Research-Extension Center, Colby Kansas.

Irrigation capacity	Preseason irrigation	Targeted plant population (1000 p/a)	Yield (lb/a)	Harvest plant population (p/a)	Heads /plant	Achenes /head	Achene Mass (mg)	Achene Oil%	Water use (inches)	Water Productivity (lb/acre-in)
1 in/4 d (13.94 in)	None	18	3145	14956	1.00	1555	61.6	39.4	24.82	126
		23	3265	16988	0.99	1497	59.6	39.8	25.89	126
		28	3315	21635	0.87	1750	52.9	41.6	24.86	133
		Mean	3242	17860	0.95	1601	58.0	40.3	25.19	129
	9.2 inches	18	3183	14985	1.00	1666	58.1	39.1	25.33	126
		23	3448	17424	0.99	1572	58.2	40.3	25.64	134
		28	3662	19689	0.99	1599	53.7	40.3	26.79	137
		Mean	3431	17366	0.99	1612	56.6	39.9	25.92	132
Mean 1 inch/4 days			**3328**	**17635**	**0.97**	**1606**	**57.4**	**40.1**	**25.52 a**	**130 c**
1 in/8 d (8.18 in)	None	18	3191	13939	1.00	1717	62.6	38.9	20.45	157
		23	3160	16698	0.99	1494	58.8	39.6	20.23	156
		28	3423	19747	1.00	1439	55.3	40.8	20.80	165
		Mean	3258	16795	1.00	1550	58.9	39.7	20.49	159
	9.2 inches	18	3148	14375	1.00	1544	65.2	39.2	18.61	172
		23	3310	17569	0.98	1495	59.4	40.1	18.37	181
		28	3480	19747	1.00	1414	58.0	41.5	18.75	187
		Mean	3313	17230	0.99	1484	60.9	40.3	18.58	180
Mean 1 inch/8 days			**3286**	**17013**	**0.99**	**1517**	**59.9**	**40.0**	**19.54 b**	**169 b**
1 in/12 d (6.26 in)	None	18	3237	14462	1.00	1610	63.8	39.1	17.41	188
		23	3126	17772	0.98	1280	64.9	39.9	17.18	183
		28	3121	18121	1.00	1490	54.5	40.0	17.43	180
		Mean	3161	16785	0.99	1460	61.0	39.7	17.34	183
	9.2 inches	18	3074	14084	1.00	1440	70.1	38.4	18.52	168
		23	3487	18992	0.99	1478	57.5	39.8	18.47	191
		28	3417	19457	0.97	1410	59.3	40.5	18.47	186
		Mean	3316	17424	0.99	1440	62.6	39.5	18.49	181
Mean 1 inch/12 days			**3244**	**17125**	**0.99**	**1450**	**61.9**	**39.6**	**17.95 c**	**182 a**
Study-Wide Mean			**3286**	**17251**	**0.99**	**1525**	**59.7**	**39.9**	**20.99**	**161**
Preseason Irrigation	**None**		**3224**	**17168**	**0.98**	**1541**	**59.2**	**39.9**	**21.22**	**156**
	9.2 inches		**3350**	**17337**	**0.99**	**1508**	**60.2**	**39.9**	**20.75**	**166**
Target plant population (1000 p/a)		**18**	**3160 b**	**14452 c**	**1.00**	**1586**	**63.7 a**	**39.0 c**	**20.83**	**156**
		23	**3294 ab**	**17530 b**	**0.99**	**1472**	**59.7 b**	**39.9 b**	**21.01**	**161**
		28	**3404 a**	**19781 a**	**0.97**	**1515**	**55.7 c**	**40.8 a**	**21.13**	**165**

Shaded items within a column are significantly different at P<0.05 when followed by a different lower-cased letter.

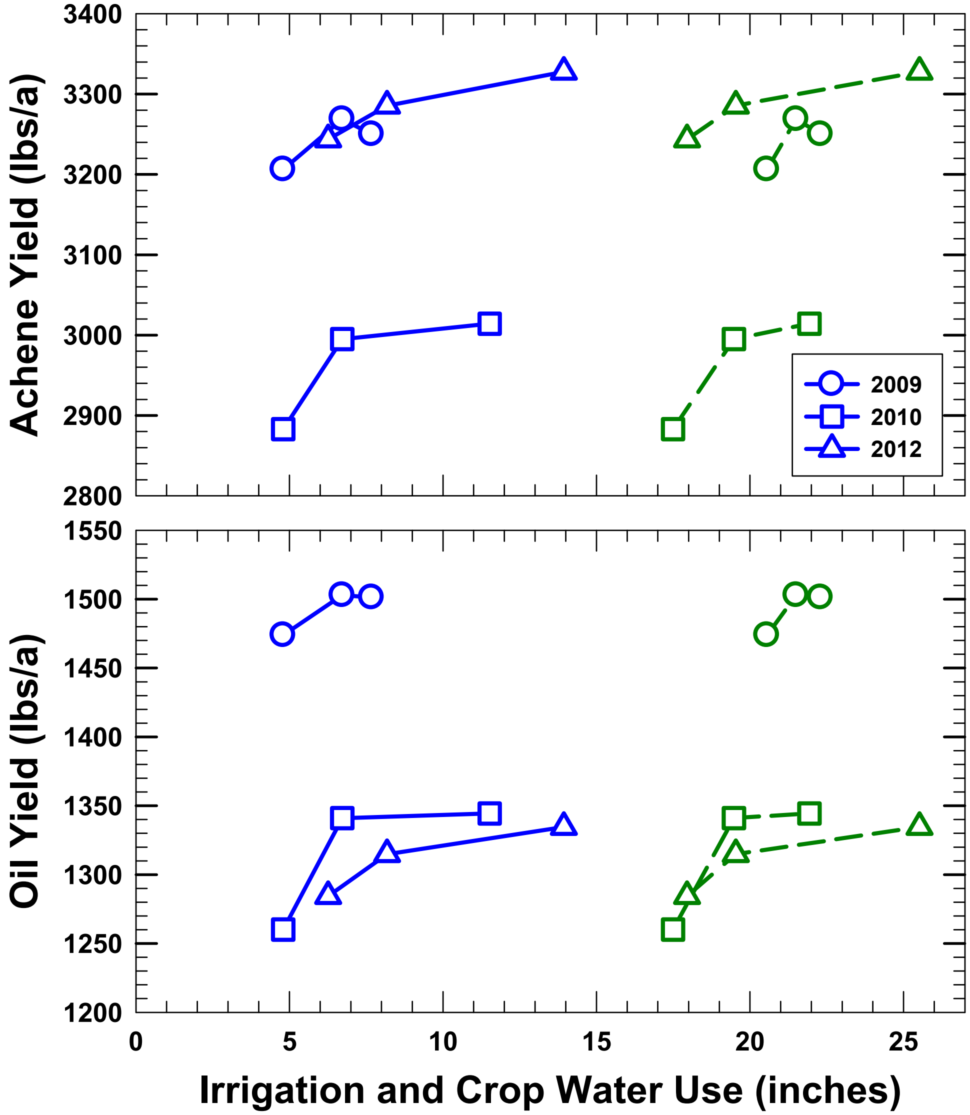

Figure 2. Achene yield and oil yield as related to irrigation amount and total crop water use in a sprinkler irrigated sunflower study, KSU Northwest Research-Extension Center, Colby, Kansas, 2009-2012. Note: Irrigation responses in blue unbroken lines and crop water use responses in green dashed lines.

Discussion

Yield – Water Use Production Function

Irrigation studies with sunflower have been conducted periodically at the KSU Northwest Research-Extension Center since 1986. The irrigation treatments in these studies varied with some studies applying various percentages of well-water crop water use (ET), some studies applying water at specific sunflower growth stages, and some studies using water budget irrigation scheduling under various irrigation system capacities. Yield response varied some from year to year and some between studies as might be anticipated, but on the average 157 lbs of sunflower seed was obtained for each acre-inch of water use above a yield threshold of approximately 3 inches (Figure 3). It can be noted that the results of the current study (2009-2012) continue to fit the linear response of the earlier studies.

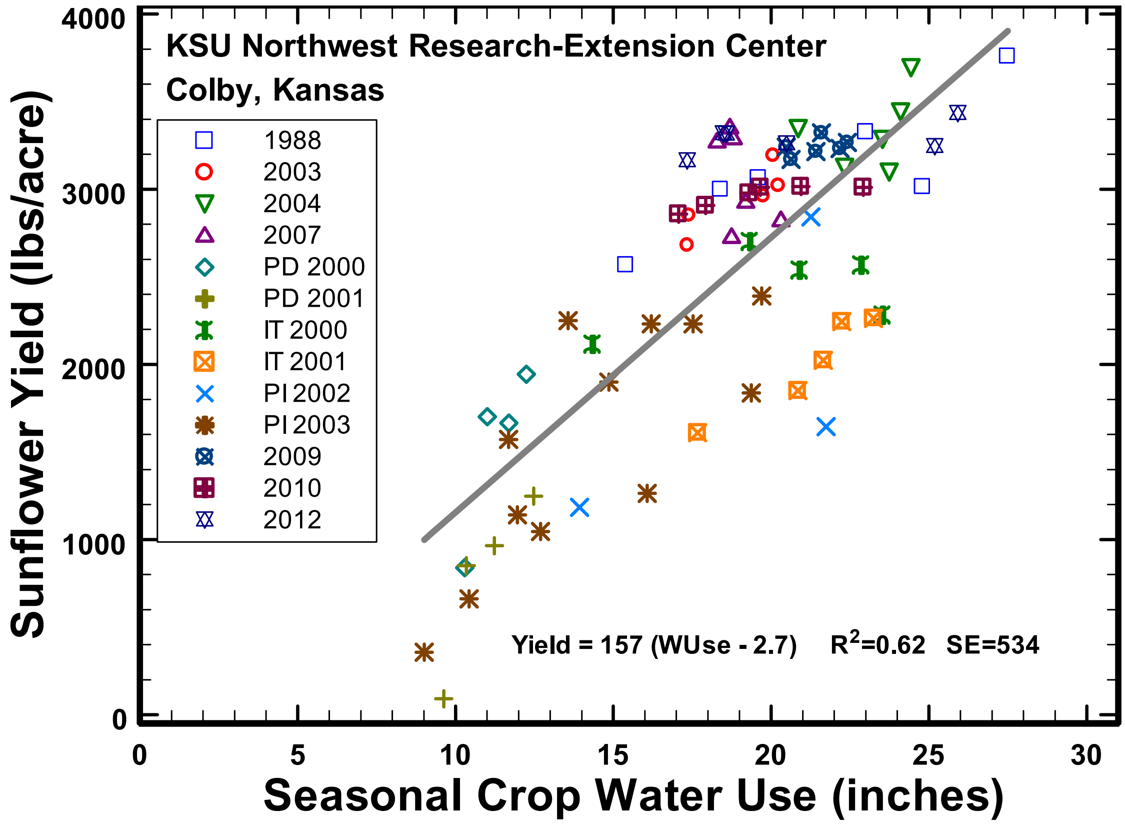

Figure 3. Sunflower yield response to total seasonal crop water use for selected studies conducted at the KSU Northwest Research-Extension Center, Colby Kansas, 1986-2007. The PD data from 2000 and 2001 was from dryland studies. The IT data from 2000 and 2001 was from studies scheduled by stage of growth. The data from the PI studies had irrigation applied at various growth periods throughout the summer. All other studies presented here were scheduled according to various percentages of crop water use or were managed according to various upper limits of irrigation capacity.

Results from Simulation Modeling

Thirty-nine years (1972-2010) of weather data was used to create simulated irrigation schedules for sunflower and also corn for a comparison crop. These irrigation schedules were also coupled with a crop yield model to estimate crop yield at various irrigation capacities (limited to 1 inch every 3, 4, 5, 6, 8, or 10 days) and under dryland production.

Although corn has greater crop water use (ET) and requires more irrigation (Figure 4) than sunflower, their peak water use rates and peak irrigation rates are very similar (Figure 5). Under full irrigation (a capacity not less than 1 inch every 4 days if needed), corn uses approximately 4.3 inches more water than sunflower during the season but only requires approximately 2.3 inches of additional irrigation because of its growth period encompasses some months of greater rainfall. Although peak ET and peak irrigation needs are similar between the two crops, sunflower's needs are for a much shorter duration and occur at a time when corn's needs are about to start declining.

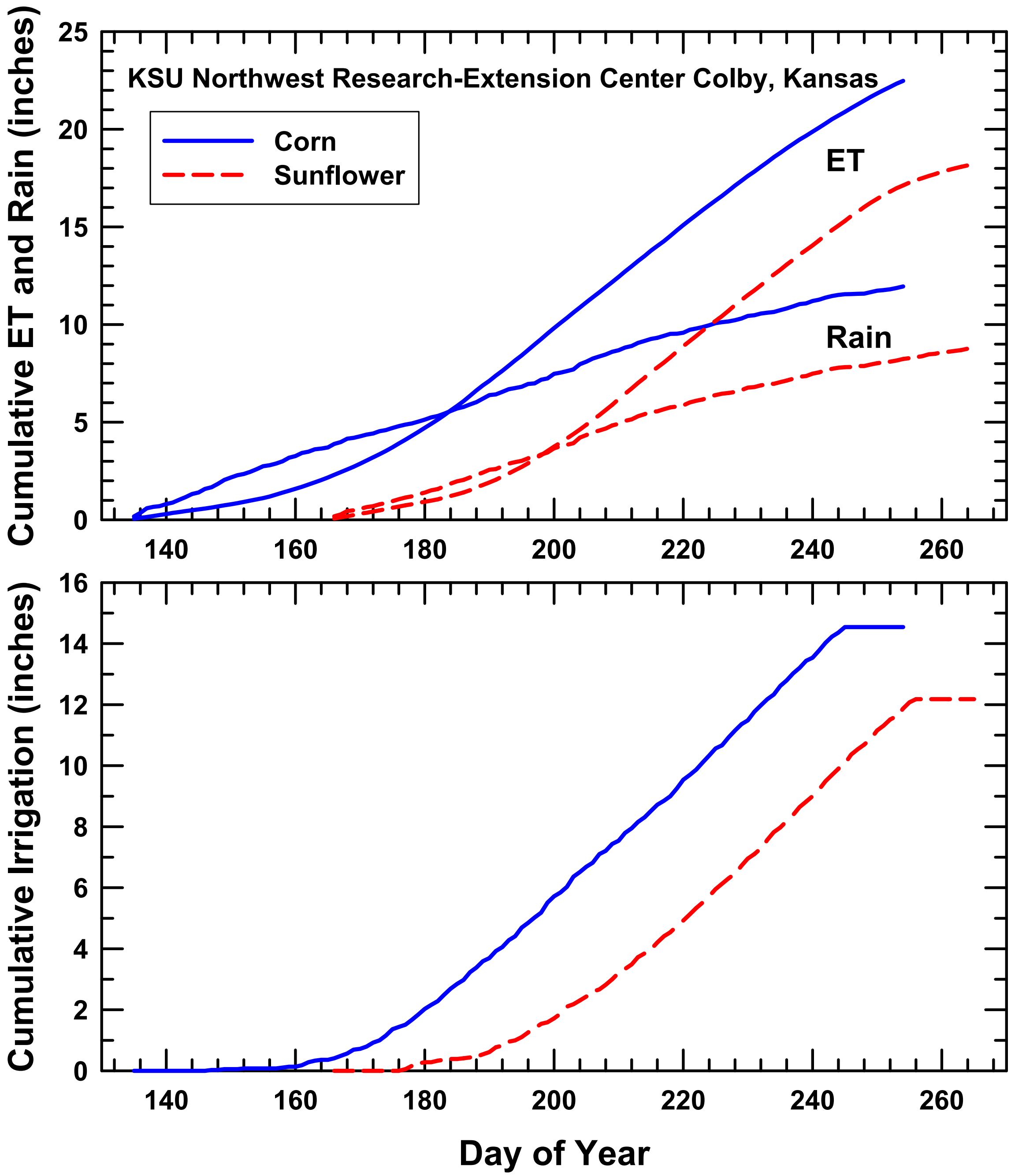

Figure 4. Simulated average cumulative crop water use (ET), rainfall and gross irrigation requirement for sunflower and corn for the 39 year period 1972 through 2010 at Colby, Kansas. Irrigation scheduling simulations were performed for sprinkler irrigation amounts of 1 inch at an application efficiency of 95%.

The shorter duration of peak ET and irrigation needs for sunflower and their occurrence at a time when peak needs for corn are about to decline open up some opportunities to shift irrigation allocations between crops. Additionally, the yield decline with just slightly deficit irrigation is usually very small with sunflowers compared to corn (Figure 6). Under the right economics, sunflower can be a good candidate for deficit irrigation.

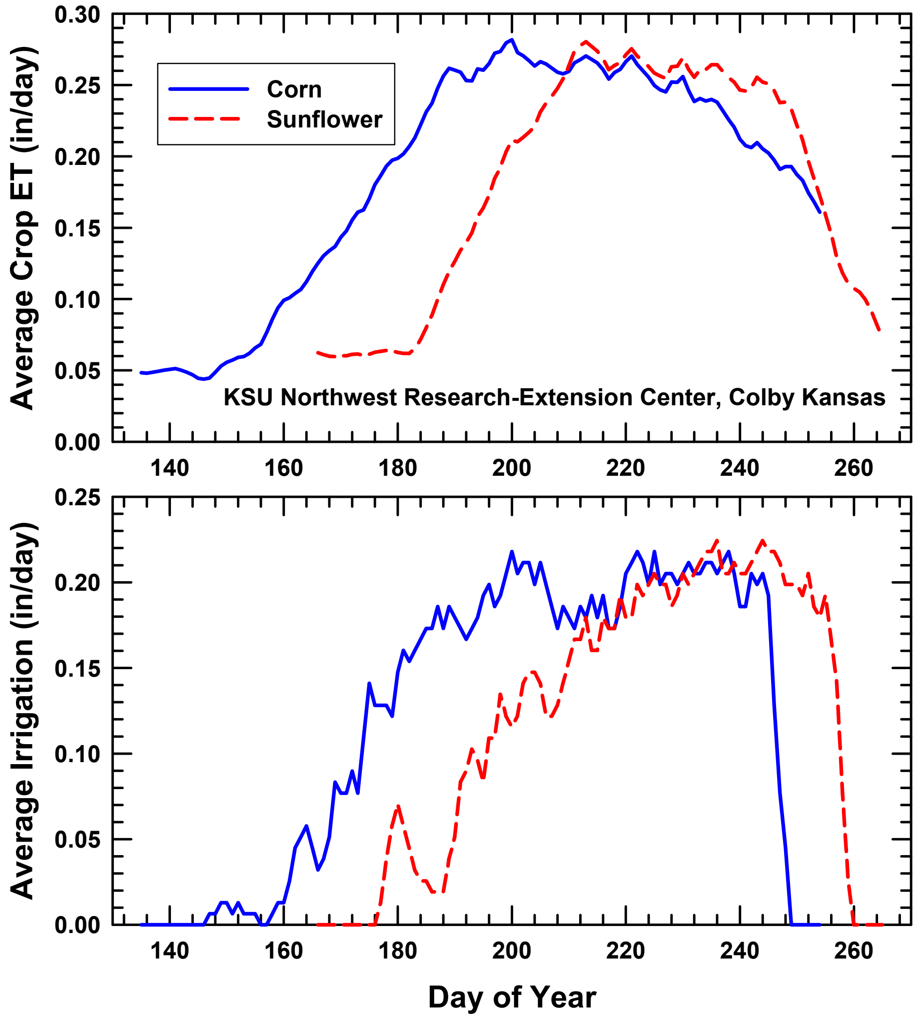

Figure 5. Simulated average daily crop water use (ET) and gross irrigation requirements for sunflower and corn for the 39-year period 1972 through 2010 at Colby, Kansas. Irrigation scheduling simulations were performed for sprinkler irrigation amounts of 1 inch at an application efficiency of 95%. The data are presented as a 4 day moving average.

As stated earlier, under full irrigation sunflower uses about 2.3 inches less irrigation than corn. However, because relative yield reductions are less for sunflower than with corn, many producers choose to deficit irrigate sunflowers and the annual irrigation difference may be 4 to 5 inches. Irrigation needs are greatest in August for sunflowers while the need is greatest in July for corn Figure 7. Some producers may want to plant a portion of their production area to sunflower to better manage their risk on lower capacity irrigation systems. However, they would be advised to estimate the economics of such a decision prior to the season. The Crop Water Allocator program (available at http://mobileirrigationlab.com/) developed by N.L Klocke and others at KSU can help with those decisions.

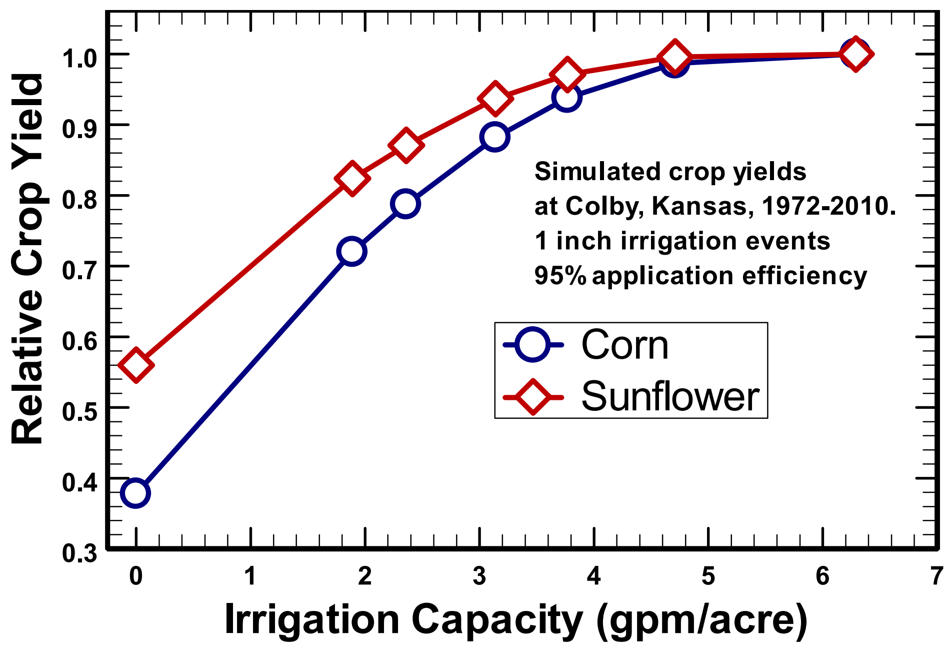

Figure 6. Simulated average relative crop yield of sunflower and corn as affected by irrigation capacity at Colby, Kansas for the 39-year period 1972-2010. Irrigation capacity data points left to right are dryland, 1 inch every 10, 8, 6, 5, 4 or 3 days, respectively. A capacity of 1 inch/4 days is equivalent to an irrigation capacity of 589 gpm/125 acre center pivot irrigation system.

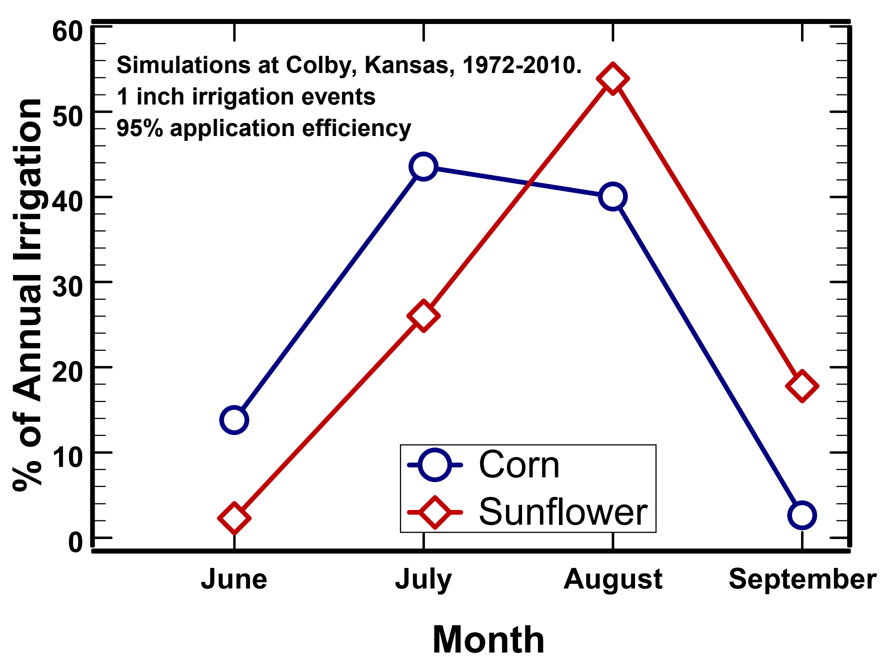

Figure 7. Average monthly distribution of irrigation needs of sunflower and corn at Colby, Kansas for the 39-year period 1972-2010 as determine from simulated irrigation schedules.

Summary and Conclusions

Sunflower was grown under sprinkler irrigation in Colby, Kansas for three very different crop years (2009, cool and wet year; 2010, near normal overall but very dry after flowering; and 2012, a severe drought year with high temperatures). Irrigation capacities were limited to not more than 1 inch every 4, 8 or 12 days but irrigation events were scheduled only as needed as determined with a weather-based water budget. Achene yield was only statistically increased by irrigation in 2010, but tended to increase numerically up through the medium irrigation level (1 inch/8 days) in all three years. Similarly, oil yield plateued at the medium irrigation level. Dormant season irrigation generally had no appreciable effect on achene yield or yield components. The optimum harvest plant population for sunflower in this study in terms of achene yield and oil yield was approximately 19,000 to 20,000 plants/acre.

The yield - water use production function for sunflowers in this region is approximately 157 lb/acre for each inch of water use above a yield threshold of 2.7 inches. Declines in sunflower yield with deficit irrigation are less drastic than with corn, so producers may wish to consider sunflower when irrigation system capacities are marginal. Sunflower and corn have similar peak ET and irrigation rate requirements for full irrigation, but sunflower requires about 2.3 inches less irrigation and its peak needs began at about the time corn needs are starting to decline. Average full irrigation of sunflowers would be approximately 12 inches, but often producers will apply between 8 and 10 inches of irrigation because the amount of yield decline is only a few percentage points.

Acknowledgements

[1] Mention of tradenames is for informational purposes only and does not constitute endorsement by the authors or by the institutions they serve.

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Simplified Irrigation Scheduling on a Smart Phone or Web Browser

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Abstract. *Irrigation Scheduler Mobile is a free and open source irrigation scheduling tool that runs on any smart phone or any web browser. The focus was placed on designing it for simplicity and intuitive usability. Setting up a field is simply a matter of naming it, selecting the nearest weather station, and choosing a crop and soil type. It automatically populates all of the necessary parameters from tables of default values for the chosen crop and soil texture. It automatically pulls weather data from any weather station in a large variety of different weather networks to calculate and use reference ET. It readily displays useful charts and tables for visual evaluation of soil water status and model inputs. It is flexible and allows educated users to change any of the model parameters. There are integrated help menus on each page. The model can be corrected using soil water measurements or estimates. It includes a one-week forecast of crop water use and soil water status for irrigation decision planning. It works with cutting dates to model forage regrowth. It can send out push notifications to growers in the form of an email or as a text message. It has many additional useful features that growers have requested. It currently works with weather networks in 11 different states. It is possible to set up different crop defaults for different climatological regions (groups of weather stations). This manual describes this tool and its use. The model is at http://weather.wsu.edu/is.*

Keywords. Irrigation Scheduling, weather networks, checkbook, mobile apps, crop coefficients.

Quick Start

The mobile irrigation scheduler is at http://weather.wsu.edu/is. To us it you must have an AgWeatherNet username and password. This is free and easily set up on the AgWeatherNet website (http://weather.wsu.edu). To start using Irrigation Scheduler Mobile point your mobile browser to above URL, and log in (Figure 1). Bookmark this page, or better yet, put a shortcut icon on your mobile device's home screen for quick access in the future (Figure 2).

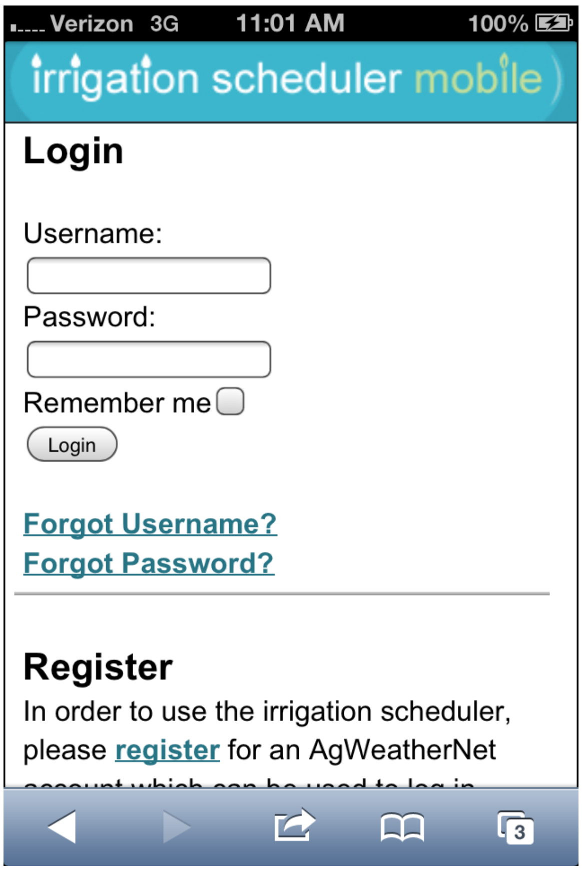


Figure 1. Login Page.

Figure 2. Bookmark or add to your home screen.

After logging in click "Add New Field" (Figure 3) to bring up the screen in Figure 4 where you can give the field a descriptive name, chose the growing year (past years are available for comparison purposes or what-if scenarios), choose the weather network from your state, select the weather station in that network that is nearest or best represents your field's growing climate, and select the crop grown and the soil texture. Click "Add Field" and you're done with the setup! Follow the on-screen instructions. Help is available for each page by clicking the "Help" link on that page.

Additional information is available below in the Using the Model / In-Depth Descriptions section.

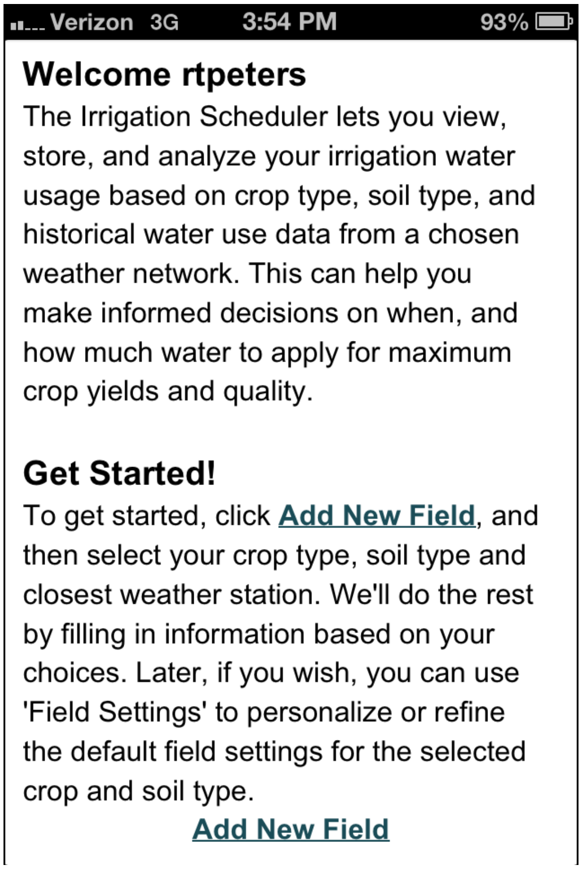


Figure 3. Welcome and Getting Started Screen

Figure 4. Add a New Field

Introduction

Irrigation scheduling is finding the answers to two basic questions: "When do I turn the water on?" and, "How long do I leave it on?" Improved irrigation scheduling has tremendous public and private benefits. It has been shown in various studies to decrease irrigation water use by 10-30% while resulting in equivalent or better crop yields and quality. Since irrigation is responsible for 80-90% of the consumptive water use in most arid areas, the total water and energy savings from improved irrigation management is tremendous. Irrigation scheduling has the following benefits:

Benefits to the grower:

- Improved crop yields,
- Improved crop quality,
- Lower pumping energy costs,
- Lower irrigation-related labor costs, and
- Decreased loss of expensive fertilizers to runoff or leaching.

Benefits to the environment:

- Less movement of fertilizers and pesticides with the water off of farms fields into streams, water-bodies, and groundwater (non-point source pollution), and
- More water remains available in groundwater and in streams for alternative uses including fish and wildlife habitat.

Benefits for energy supply:

- Decreased irrigation energy pumping costs (typical values are 10-20% savings), and
- Water remains in rivers to drive power-generation turbines at multiple dam sites.

There are many irrigation scheduling tools available including paper-and-pencil versions (e.g. Wright, 2002), spread sheet versions (e.g. Clark et al., 2001), compiled program versions (e.g. Rogers et al., 2009), and online versions (e.g. Hillyer and English, 2011). However these tools are not widely used and most of them are not readily adaptable to the Pacific Northwest State. The most common reason cited for not using these tools is that they are difficult to learn, time consuming to use, and that the grower does not feel that it is worth this time and effort required. Agricultural producers are also rarely in the office and don't get many chances for, and tend to not enjoy doing "desk-work." A simple and user-friendly irrigation scheduling tool that is accessible from a smart phone that is already in most producer's pocket is needed to increase the adoption of data-based irrigation scheduling.

Irrigation Scheduler Mobile is a soil water balance model that meets these requirements. It is a free irrigation scheduling tool developed by Washington State University that is designed for use on a smart phone or on a desktop web browser for doing simplified check-book style irrigation scheduling. It is a basic soil water budget model.

In addition Irrigation Scheduler Mobile has the following features:

- It is simple to set up and intuitive to use.
- There are integrated help menus on each page.
- It uses tables of default crop and soil parameters to simplify setup
- It automatically pulls daily crop water use (evapotranspiration, or ET) estimates from a chosen weather station in a fairly expansive number of agricultural weather networks.
- It readily displays useful charts and tables for visual evaluation of soil water status and model inputs.
- It is flexible enough to allow modifications by educated users for improved accuracy.
- The model can be corrected using soil water measurements or estimates.
- It includes a one-week forecast of crop water use and soil water status for irrigation decision planning.
- It works with cutting dates to model forage regrowth.
- Growers can interact with it in terms of hours of irrigation run time or in inches of water applied. Simple calculators are included to help calculate irrigation application rate if required.
- A correction for the smaller active soil volume due to un-irrigated inter-rows is included.
- Soil water can be displayed as a percent of the total available water (100% = full, 0% = empty), or as volumetric soil water content (water's percentage of the total soil volume) for better comparison with soil moisture sensors.
- It can send out push notifications to growers in the form of an email or as a text message.
- When adding a new field you can copy settings from an existing field.
- Since it is designed as a web application, it can be run on any mobile phone platform with internet access, or directly from a full sized computer web browser.
- There is a full-size computer web browser interface from http://weather.wsu.edu.
- You can download all of the data to a comma-separated variable (csv) file for more detailed analysis.
- It can do use reporting of the number of days each field was viewed and or edited by month. This was requested for cost-share documentation.
- It is possible to set up different crop defaults for different climatological regions (groups of weather stations).

Background Information and Model Assumptions

Soil serves as a reservoir to store water and nutrients for use by the plant. Knowing when to irrigate and how much water to apply requires knowledge of three things:

1. How much water can the soil hold?
2. How much water is the plant using?
3. At what point (soil water content) will the plant begin to experience water stress?

Let's discuss each of these separately.

How Much Water Can the Soil Hold?

Water is held in the empty spaces between soil particles. When these empty spaces are completely filled, the soil is said to be saturated (Figure 5). Excess water will drain out over time until a point where the soil can hold a certain amount of water indefinitely against the downward pull of gravity. This soil water content is the soil's *full* point called ***field capacity (FC)*** and in this application is measured in inches of water per foot of soil depth. The excess water that drains will move down to lower soil layers. Applying more water than a soil can retain in the plant's managed root zone results in water loss to ***deep percolation (DP)*** or "deep water loss". Water loss to deep percolation wastes water, pumping energy, and vital plant nutrients that are held in the soil water solution.

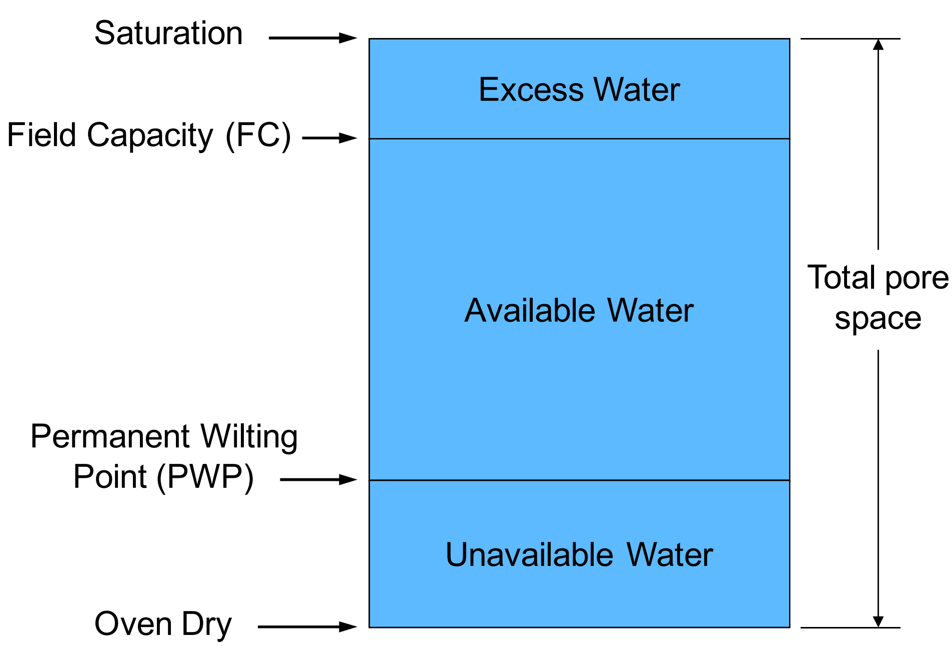


Figure 5. The various components of the soil water content.

As a plant's roots remove water from the soil, the soil dries out to the point where the suction or pull of the soil on the water is greater than the plant's ability to absorb water. At this point the plant will wilt and die. Although there is water left in the soil, from the plant's perspective the soil is *empty.* This soil water content is referred to as the ***permanent wilting point (PWP)*** and is also measured in inches of water per foot of soil depth. The difference between field capacity and permanent wilting point is known as the ***available water-holding capacity (AWC)*** again given in inches of water per foot of soil depth.

$$AWC = FC - PWP$$

Different soils have different available water-holding capacities. For example, sand cannot hold as much water as a silt soil. The default values of FC, PWP, and AWC that are used in this model for different soil textures are given in Appendix A.

A plant's rooting depth is also an important consideration. A plant with deeper roots has access to much more soil and consequently has a larger reservoir of soil water to draw upon compared to plants with shallower roots. The FC, PWP, and AWC are multiplied by the rooting depth to get the *amounts* of water held at those points in inches. Rooting zone depths change over time as the plant and its roots grow. Root growth in Irrigation Scheduler Mobile is assumed to increase linearly from a beginning depth at the planting or emergence date and is assumed to reach their maximum depth at the same time the crop canopy reaches full cover or covers (shades) 70-80% of the field area (Figure 6). After this time the root depth is assumed to remain constant until the end of the growing season.

Default values for the parameters that define the changing root zone depth for the various crops are given in Appendix B.

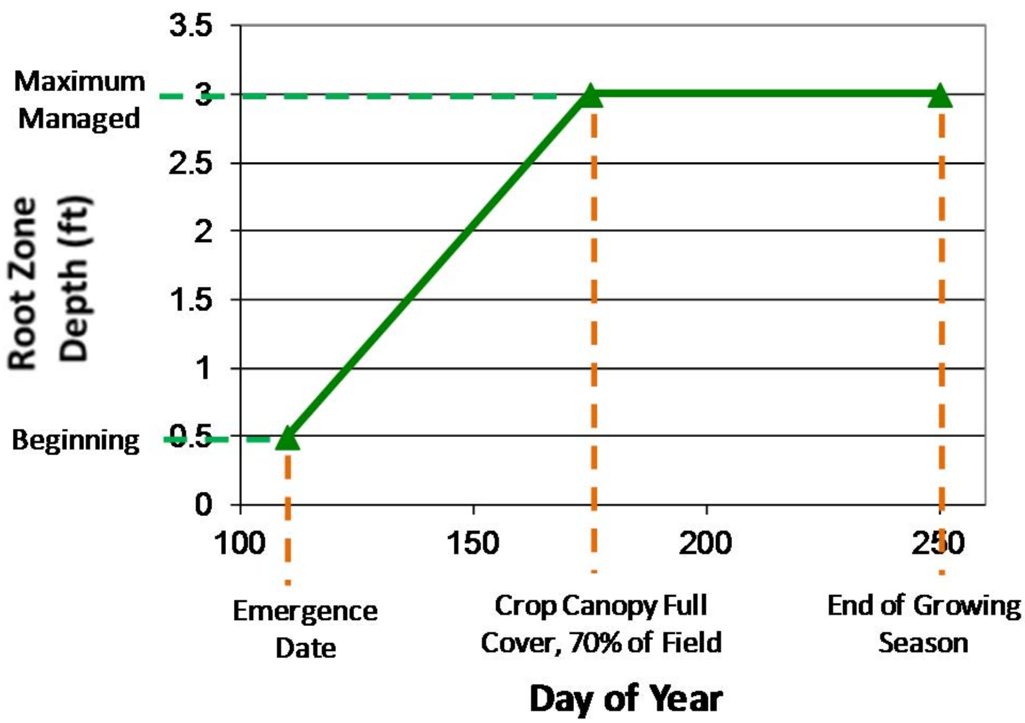


Figure 6. Parameters that define the changing root zone depth. Defaults values for these parameters are set based on the crop chosen, but can be modified in “Advanced Field Settings.”

How Much Water is the Plant Using?

The amount of water required to grow a crop consists of the water lost to evaporation from a wet soil surface and leaves, and transpiration of water by the plant. Together these are called ***evapotranspiration (ET)*** and are also referred to as crop water use. ET is measured in inches of water used per day. The crop evapotranspiration (ET_c) is calculated as:

$$ET_c = K_c \times ET_r$$

where ET_r is the estimated evapotranspiration of a reference surface of full grown alfalfa that is calculated from measured weather data. The weather data used to calculate ET_r include solar radiation, air temperatures, humidity, and wind speed data. Irrigation Scheduler Mobile uses alfalfa reference ET_r as calculated by the ASCE standardized Penman-Monteith Equation (ASCE – EWRI, 2005). K_c is a crop coefficient specific to a crop and that crop's growth stage over the season. Crop coefficients Irrigation Scheduler Mobile are mean crop coefficients and defined as in the FAO-56 publication (Allen et al., 1998; Figure 7). Default dates and crop coefficient values for different crop s are given in Appendix B.

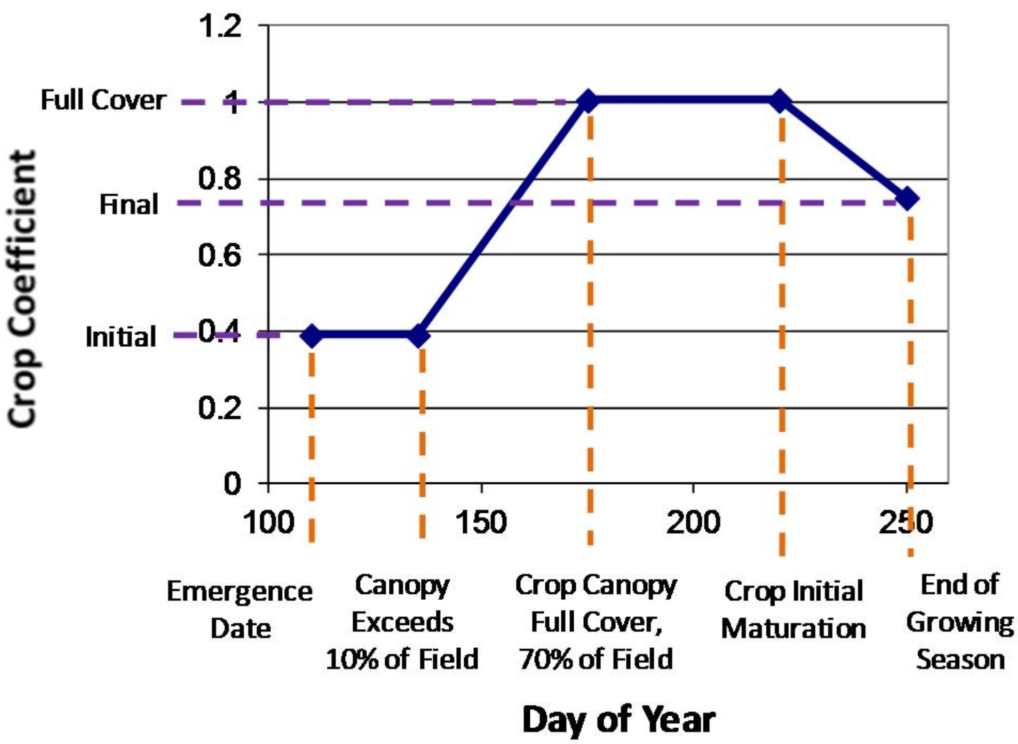


Figure 7. Parameters that define the crop coefficient curve.

At What Point Will the Plant Experience Water Stress?

As water is removed from the soil through ET there is a point below which the plant experiences increasing water stress. This point is known in this model as the first stress point or more generally as the ***management allowable depletion (MAD)***. To manage the soil water for maximum crop growth, depletion below this point is undesirable. As the soil water content decreases below MAD the stomata in the plant leaves will begin to close, the leaves will often curl or droop, and the plant will use less water and the growth will decrease. *The model estimates this decrease in water use according to Figure 8.* Daily crop water use is proportionately decreased as the % of available water decreases below MAD towards the PWP. This follows the water stress coefficient (Ks) concept as described by Allen et. al. (1998). Irrigation scheduling for maximum crop growth requires maintaining the soil water content between field capacity and the MAD.

Different plants are more resistant to water stress than others and therefore the MAD for each crop may be different. The default MAD values for the various crops are given in Appendix B.

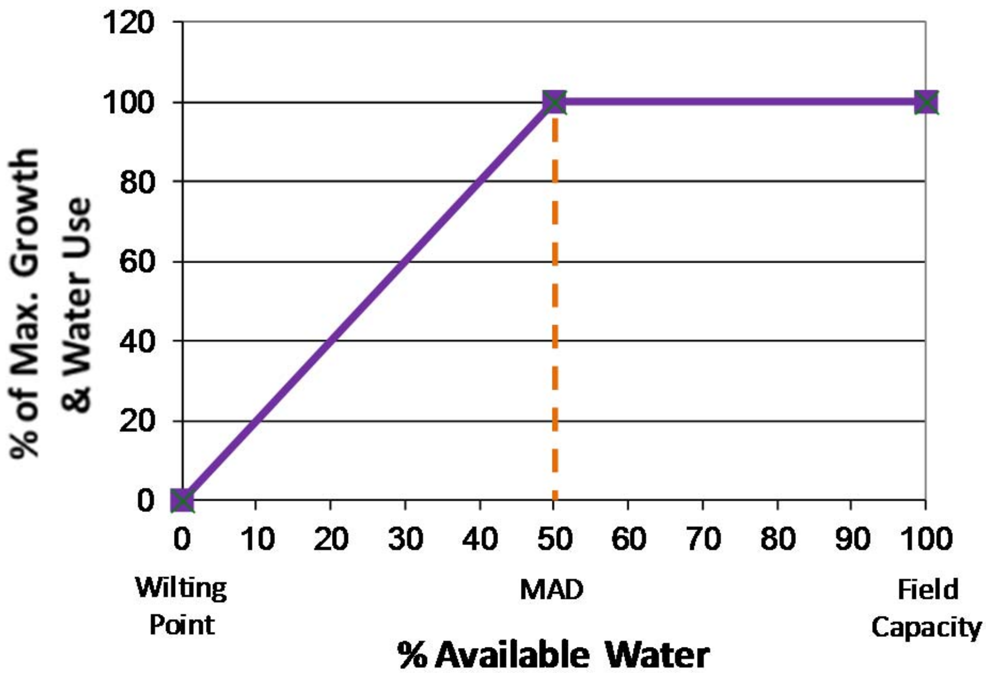


Figure 8. Water use is proportionately decreased as the % of available water goes below the MAD. Yield is also assumed to decrease in the same pattern. Defaults values for MAD is set based on the crop chosen, but can be modified in "Advanced Field Settings."

Other Model Assumptions

The following additional assumptions are made by this soil water balance model.

- All water entered as an irrigation amount infiltrates into the soil.
- Water in the plant's root zone is equally available to the plant regardless of depth.
- The season begins with a full soil profile (at field capacity). This can be modified by using the "Reset/ Correct Soil Water Availability" option on the first day in the Daily Budget table. Plant roots grow into soil at field capacity.
- Water moves quickly into the soil and excess water is lost quickly to deep percolation.
- All rainfall goes towards satisfying the calculated ET demand.

Using the Model / Page Descriptions

7-Day Daily Budget Table

The Daily Budget Table screen (Figure 9) shows the most relevant values from a daily soil water budget and allows the user to edit the inputs for each day using the “Edit” link.

The data in each column is described below:

Water Use (in/day): This is the daily crop water use (evapotranspiration or ETc) estimated from measured weather parameters from the selected weather station, and the entered crop coefficients. This model uses alfalfa reference evapotranspiration calculated using the standardized ASCE Penman-Monteith method. The model gets the weather data from the weather network when the model is first opened, if it has been greater than two hours since the data was pulled, or after a change is made in Field Settings. Because of this, if the weather network managers make corrections to the historical data for that weather station, these changes are reflected in the model.

Rain& Irrig. (in): This is the sum of the measured rainfall at the weather station for that day and/or and the irrigation amount. Irrigation events must be entered using the Edit link. This is net irrigation, not gross. Some applied irrigation water is lost to evaporation. Therefore gross irrigation amounts must be discounted for irrigation efficiency. Typical irrigation efficiency values are: drip-95%, center pivot-85%, wheel/hand lines/lawn sprinklers-70%, big guns-60%. For example a gross depth of 1 inch of water is applied by a center pivot, enter 0.85 here (1 inch x 85%/100). If you use measured application depths, don’t correct for efficiency. *For surface irrigation, a reasonable assumption is that you completely refill the soil to field capacity, or replace the soil water deficit.*

Soil Water (%): This is the calculated daily soil water content expressed as a percent of the available soil water. 100% is equivalent to field capacity, and 0% is equivalent to wilting point. Entering a measured or estimated soil moisture value here (using the Edit link) will correct the model to the entered value from that day forward. Volumetric soil water content for comparison with soil moisture sensor readings is available in the expanded information (click the date; Figure 13).

Water Deficit (in): The soil water deficit in the root zone. This is the amount of "space" in the soil, or the depth of irrigation water that can be applied before the soil is full again (reaches field capacity).

Edit Data: Use this link at each line to add irrigation amounts or correct the model for measured soil water contents (Figure 11).

Some descriptions of how the page operates:

Line Colors: When the calculated soil water content is well above the MAD point and the plant growth should be at maximum, then the row is highlighted green (Figure 9). When the soil water content gets close to the MAD line (only 15% of the readily available water remaining) then the row turns yellow. And when the soil water content goes below the MAD line the row is highlighted red as a warning of crop water stress.

The Most Important Number: The most important value for irrigation scheduling is *this morning's soil water deficit*. This is the amount of water that I need to apply today to completely refill my soil profile. If I apply more water than this, some will be lost to deep percolation because the soil can't hold it all. It is highlighted in **red** (can be seen in Figure 13).

Navigation: You can navigate to other dates in the growing season using the buttons at the bottom of the table. The date button in the middle is used to go to the week starting with the chosen date (Figure 10). Note that you cannot navigate outside of the growing season as defined by the crop's planting date and end-of-season or harvest date as defined in Field Settings. The |<< and >>| buttons takes you to the beginning of the growing season and to today (or to the growing season) respectively. The <<< and >>> buttons navigation you forward or backwards respectively in time by one week.

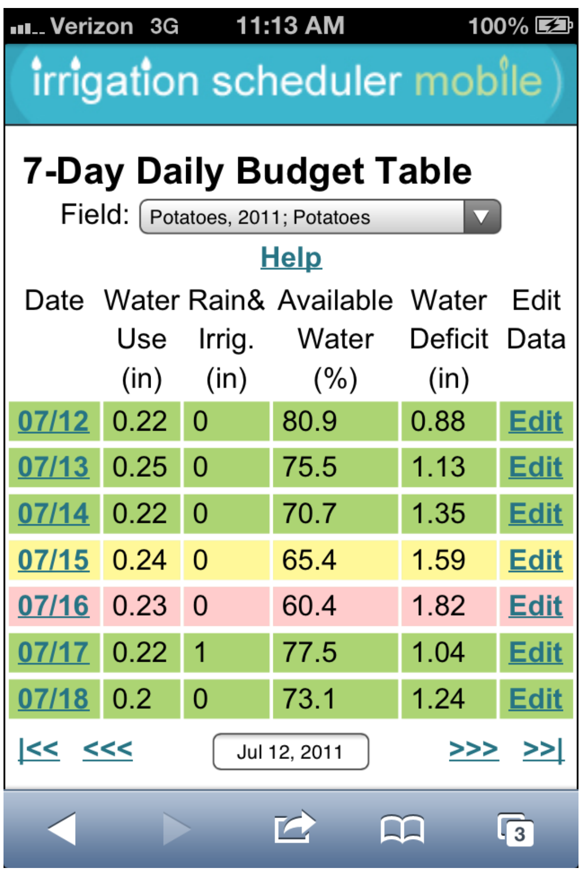


Figure 9. Daily Budget Table screen

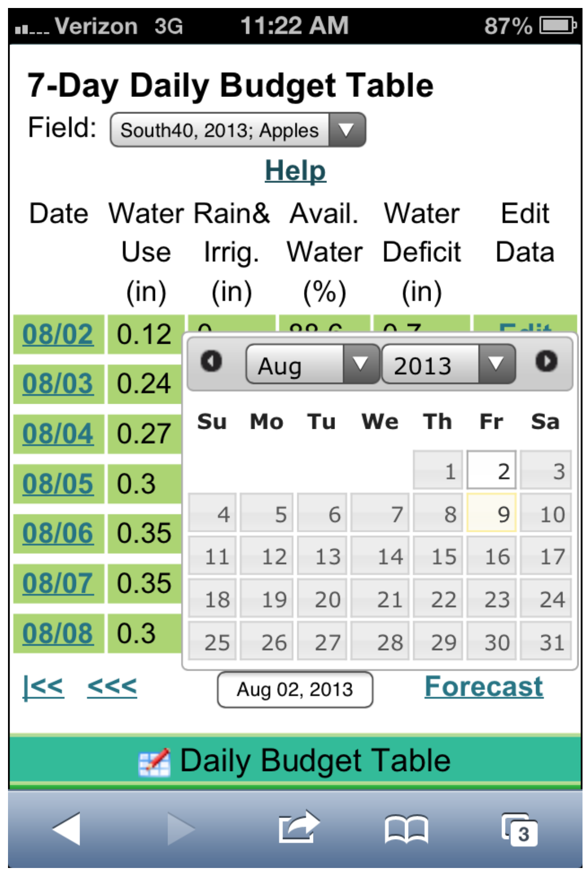


Figure 10. Choose first date of week to view.

Forecast: The last day on the Budget Table represents very early this morning. A seven-day forecast is available. This forecast is based on the projected maximum and minimum temperatures from the National Weather Service (NWS) for those days at the latitude and longitude of the chosen weather station. The Hargreaves equation is used with these temperature data to estimate grass reference ETo which is then multiplied by 1.2 for alfalfa reference ETr which is used in the model. If the model is viewed late in the day, the 7th forecasted day is from the NWS. However before 6 PM the 6th forecasted day is repeated for the 7th forecasted day. Irrigations can be entered in the future to do planning. These irrigation events will remain as time passes from the future to the past. Historical ET information always overwrites forecasted values. Forecast values are pulled when the field is first viewed, once every two hours, or after a change is made in Field Settings.

Edit Data: Clicking the Edit link on that day expands the screen to accept inputs for that day as shown in Figure 11. From here you can add or edit irrigation amounts, or reset or correct the soil water availability to make it better match reality based on observations or soil moisture measurements. Click Cancel closes the table up again. You must click Save for these changes to be applied.

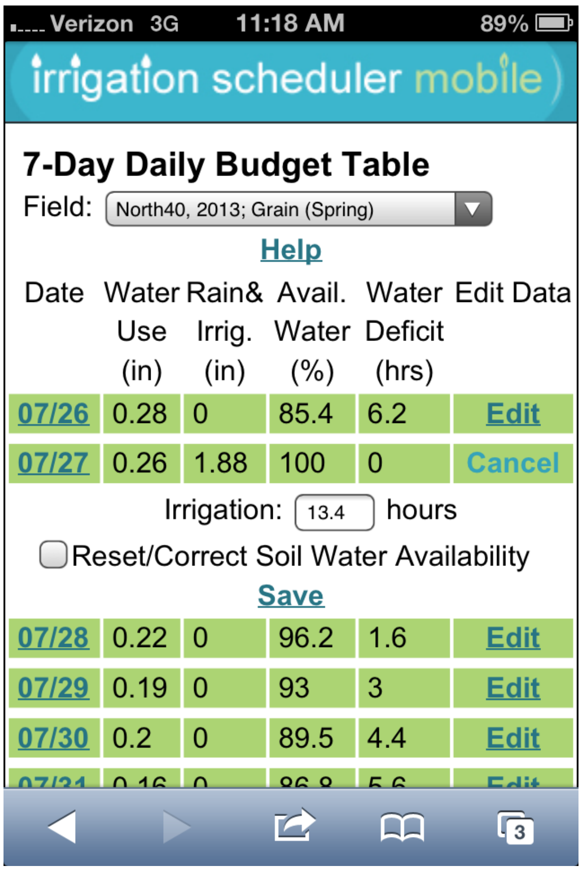


Figure 11. Edit button expands table for inputs.

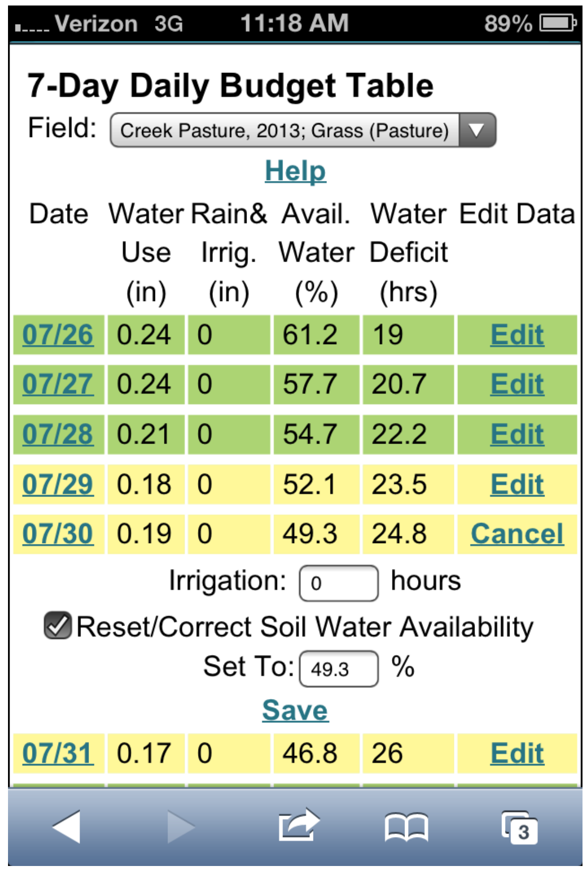


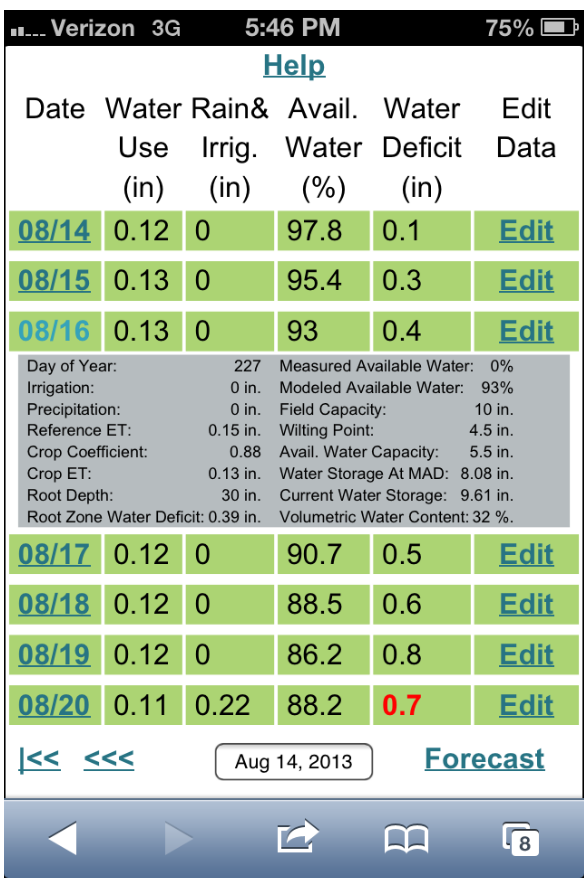
Figure 12. Reset/Corrective Soil Water Availability

Irrigation: Enter the net amount of irrigation applied to the field on this date. If you chose to use hours instead of inches in Field Settings then you can enter this value in hours of irrigation run time. Some applied irrigation water is lost to evaporation. Therefore *gross irrigation amounts must be discounted to account for irrigation inefficiency*. This is done by multiplying by the irrigation efficiency as a decimal (% / 100). Typical irrigation efficiency values are: drip-95%, center pivot-85%, wheel/hand lines/lawn sprinklers-70%, big guns-60%. For example, a gross depth of 1 inch of water is applied by a center pivot, enter 0.85 here (1 inch x 85%/100). If you use measured application depths, don't correct for efficiency. For surface irrigation, either use a very large number (like 3-4 inches at each irrigation) or a reasonable assumption is that you completely refill the soil to field capacity to 100% Available Water, or completely replace the soil water deficit.

Reset/Correct Soil Water Availability: Check this box to overwrite the calculated percent of available soil water with an entered number (Figure 7). You might want to do this to correct the model to make it better match observations or a soil moisture measurement. The model will use your entered value as the new value and will calculate the estimated soil water content from that point on. Unchecking this box will make model return to the calculated value.

Correcting Rainfall (in): Measured rainfall is automatically included from the weather station. If you measured rainfall at your field and it differs significantly from the existing value, you can correct it by adding *the difference* as an irrigation. If you measured less rainfall than the weather station reported, you can subtract the difference by adding this difference as a *negative* irrigation value. It makes the soil water chart look funny to plot that negative value, but the math works correctly.

Additional Details: Additional details of the daily soil water budget are available by clicking on the date (Figure 13). This will expand the table to show these details. The table can be returned to normal again by clicking the date again.



Date	Water Use (in)	Rain& Irrig. (in)	Avail. Water (%)	Water Deficit (in)	Edit Data
08/14	0.12	0	97.8	0.1	Edit
08/15	0.13	0	95.4	0.3	Edit
08/16	0.13	0	93	0.4	Edit

Day of Year:	227	Measured Available Water:	0%
Irrigation:	0 in.	Modeled Available Water:	93%
Precipitation:	0 in.	Field Capacity:	10 in.
Reference ET:	0.15 in.	Wilting Point:	4.5 in.
Crop Coefficient:	0.88	Avail. Water Capacity:	5.5 in.
Crop ET:	0.13 in.	Water Storage At MAD:	8.08 in.
Root Depth:	30 in.	Current Water Storage:	9.61 in.
Root Zone Water Deficit:	0.39 in.	Volumetric Water Content:	32 %.

08/17	0.12	0	90.7	0.5	Edit
08/18	0.12	0	88.5	0.6	Edit
08/19	0.12	0	86.2	0.8	Edit
08/20	0.11	0.22	88.2	0.7	Edit

Figure 13. Clicking on the date expands the table to show additional details for that date.

Soil Water Chart

The soil water chart (Figure 14) shows the estimated soil water content (blue line) over time in relation to the field capacity (light green line), management allowable depletion (MAD; red line), and the wilting point (**black line**). All of these may change over time as the soil volume available to the plant increases with the growing plant roots (i.e. the upwards slopes in the first part of the season).

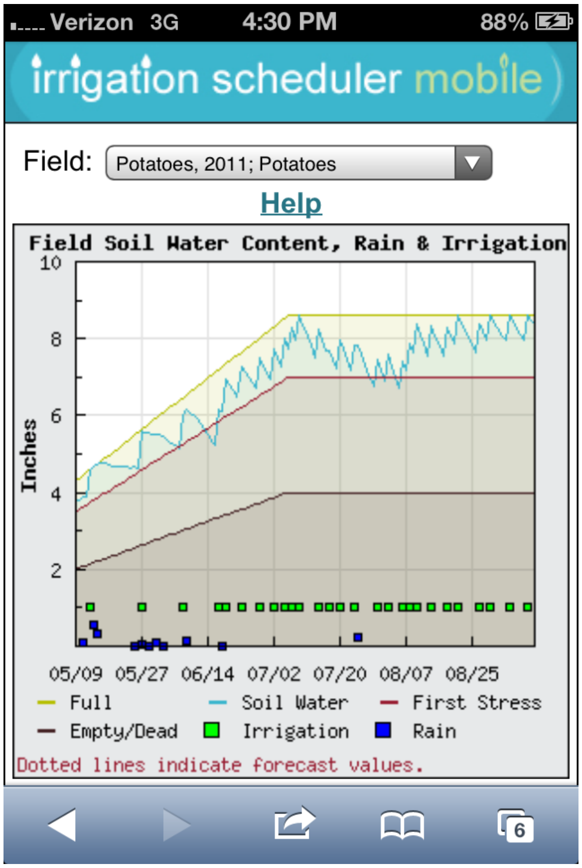


Figure 14. Soil Water Chart

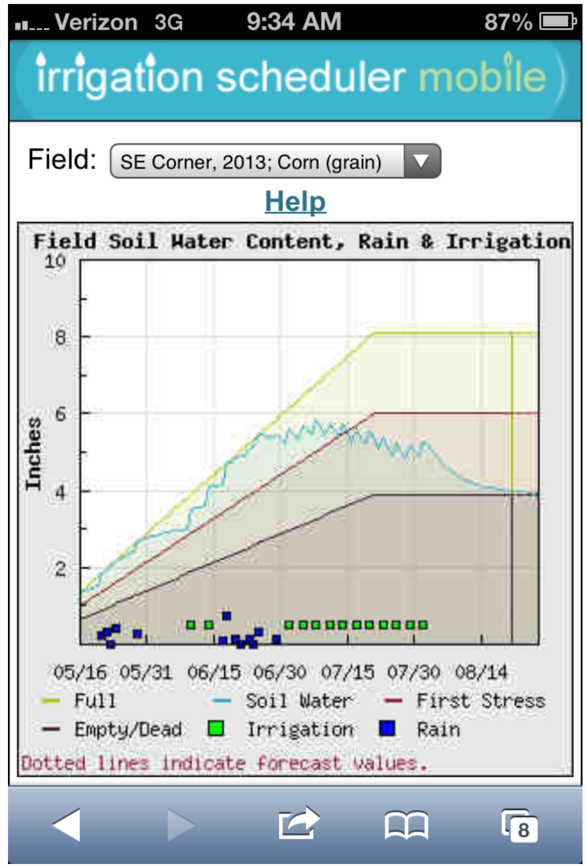


Figure 15. Shows how water stress (below the MAD line) causes daily water use to decrease.

Enter irrigation events (green points), or correct the estimated % available water content based on soil moisture measurements or estimates in the "Daily Budget Table" to make the soil water content better represent your field conditions. Rainfall amounts are pulled from the weather station (blue points). If you find that this model is consistently off, try editing the dates and crop coefficients in "Field Settings".

Figure 15 is an example of a field where the irrigation system cannot keep up with crop water use demands and also shows how the model will modify daily crop water use numbers using the assumptions illustrated by Figure 5. As the soil dries below the First Stress (MAD) point, the *rate* of drop in the soil water content decreases over time as the plant shuts down.

For maximum crop growth and production keep the soil water content (blue line) between the Full point, or field capacity; top green line) and the and the First Stress (MAD, middle red line).

More Charts

Clicking the "More Charts" button will give you access to the additional charts shown in Figure 16 that help you understand and evaluate your field and your soil water balance model. Clicking "Less Charts" hides these charts again.

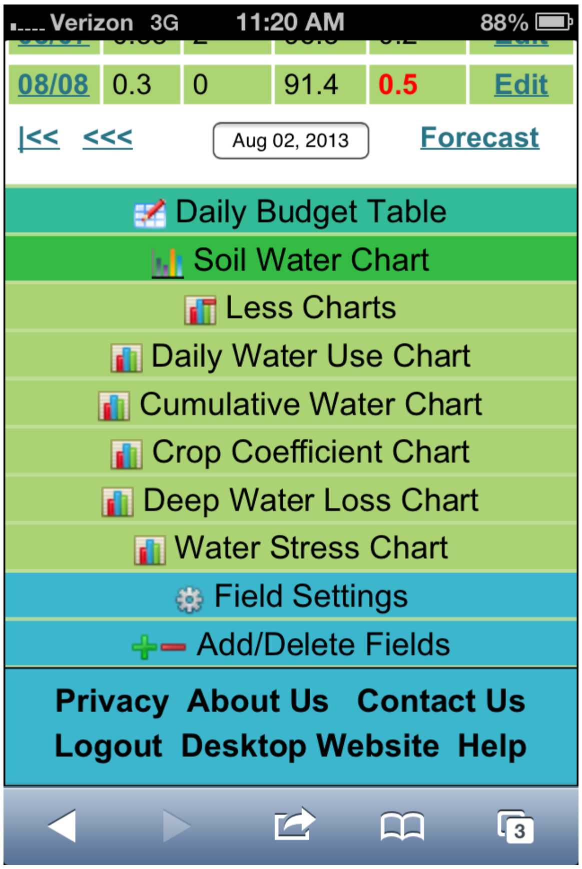


Figure 16. Clicking More Charts

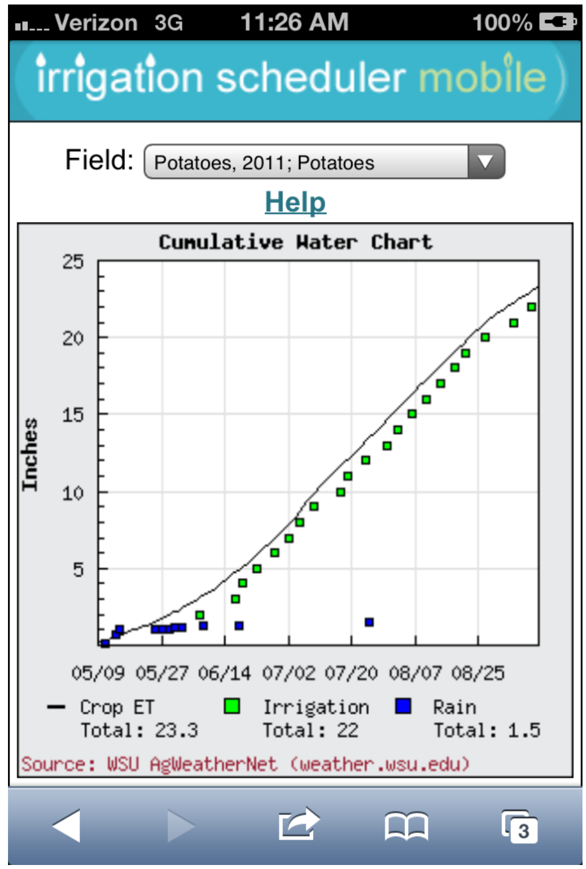


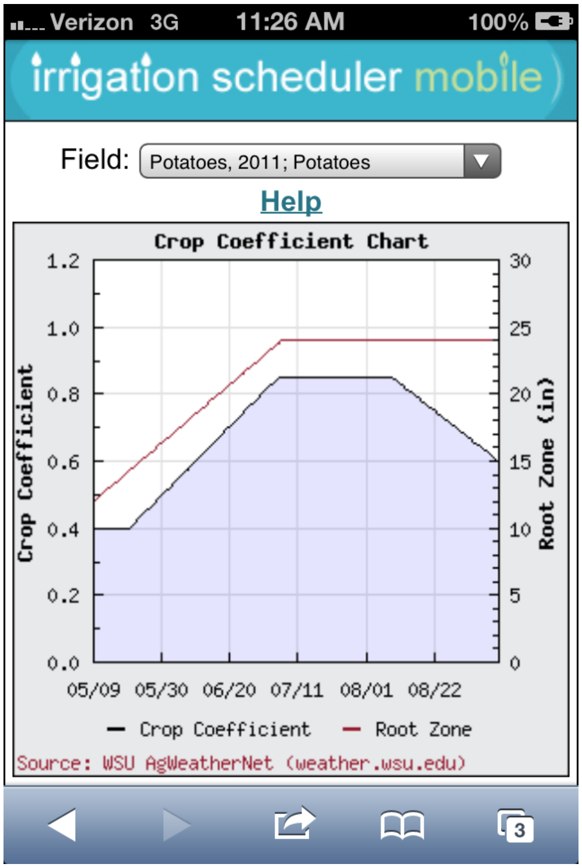
Figure 17. Cumulative Water Chart

<u>Cumulative Water Chart</u>

Figure 17 shows the cumulative crop evapotranspiration (ETc, or crop water use), irrigation, and rainfall over the specified growing season. The season totals are given in the chart legend.

<u>Crop Coefficient Chart</u>

Crop coefficients (Kc) are multiplied by the daily reference alfalfa evapotranspiration (ETr) rate that is calculated from the measured weather parameters from your chosen weather station. The Crop Coefficient Chart (Figure 18) shows the crop coefficient curve used for this field over the growing season. Also shown is the root zone depth over time. The values that define these curves can be viewed and edited on the “Advanced Field Settings” page



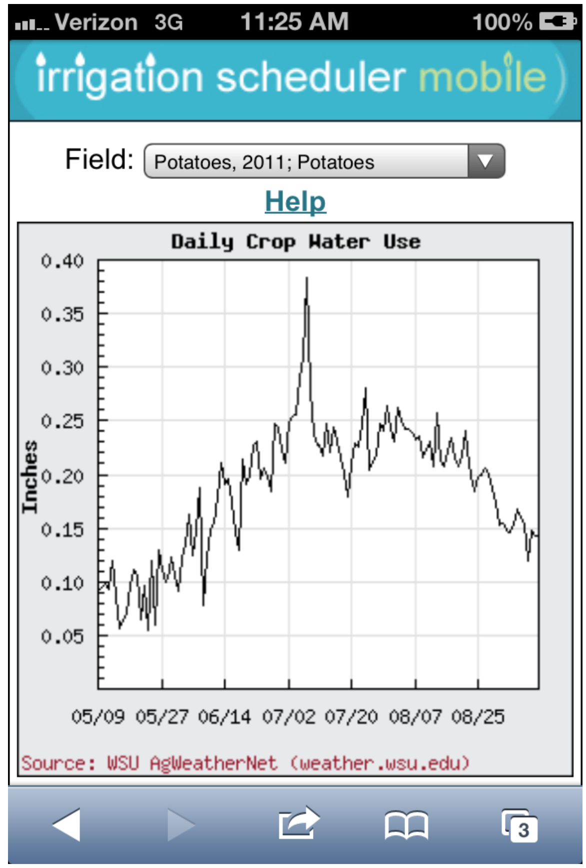


Figure 18. Crop Coefficient and Root Depth Chart.   Figure 19. Daily Crop Water Use Chart

Daily Water Use Chart

The Daily Water Use Chart (Figure 19) shows the daily crop water use (evapotranspiration, or ETc) over the specified growing season. This is calculated as ETc = ETr x Kc where ETr is alfalfa reference evapotranspiration and Kc is the crop coefficient for that day. These values are affected by the weather (hot, dry, sunny, and windy days cause the plants to use more water), the crop coefficients, and the water stress status of the plant (below MAD, the crop water use is proportionately decreased as described in the user’s manual).

Deep Water Loss Chart

When more water is applied than can be held in the root zone (soil water content exceeds field capacity), then this water moves down past the bottom of the root zone and is lost to deep percolation. The deep water loss chart (Figure 20) shows the cumulative water losses to deep percolation.

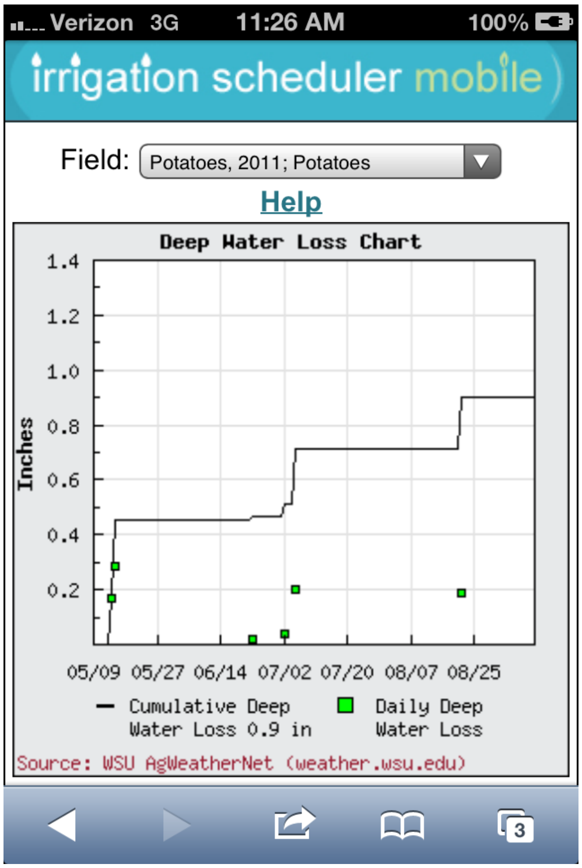


Figure 20. Cumulative Deep Water Loss

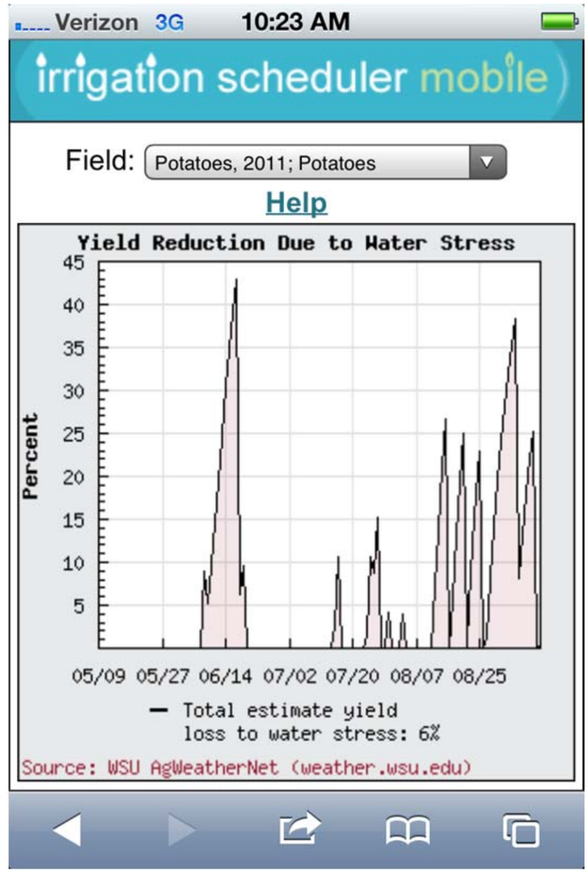


Figure 21. Corresponding Water Stress Chart

Water Stress Chart

This model uses a very simplified method of yield loss estimation. When the soil water content goes below the red MAD line as in Figure 21 it is assumed that there is yield loss that is equivalent to the amount of decreased water use similar to Figure 5. In other words:

$$\frac{Y}{Y_m} = \frac{ET}{ET_m}$$

Or solved for yield,

$$Y = Y_m \times \frac{ET}{ET_m}$$

where Y is the actual crop yield, Y_m is the maximum obtainable crop yield, ET is the actual crop water use, and ET_m is the maximum possible crop water use. The right-hand portion of this equation can be simplified as a crop water stress coefficient (K_s) that behaves as shown in Figure 8 as:

$$K_s = \frac{ET}{ET_m}$$

The % yield reduction on any particular day is therefore (1-Ks) × 100%. This is what is charted (Figure 21).

The season-long total estimated yield loss due to water stress as shown on this chart is therefore calculated using the season-long mean K_s (K_{sm}) as:

$$(1 - K_{sm}) \times 100\%$$

Field Settings

Field Settings allows users to select model interaction options and to change the field defaults that were chosen based on the crop and soil type chosen during field setup. Default values for each crop and soil are in Appendix A & B. Entering alternate values here overwrites these defaults. *The "Update Field" button must be clicked for any changes to be applied.*

Additional information about each option follows:

Show Forecast Values: If checked, the model will get a seven day forecast of the maximum and minimum temperatures from the National Weather Service based on the location of the chosen weather station. The Hargreaves equation is then used to estimate grass reference evapotranspiration (ETo) and multiplied by 1.2 to estimate alfalfa reference evapotranspiration (ETr). Forecasts are refreshed every 2 hours. (See Figure 23)

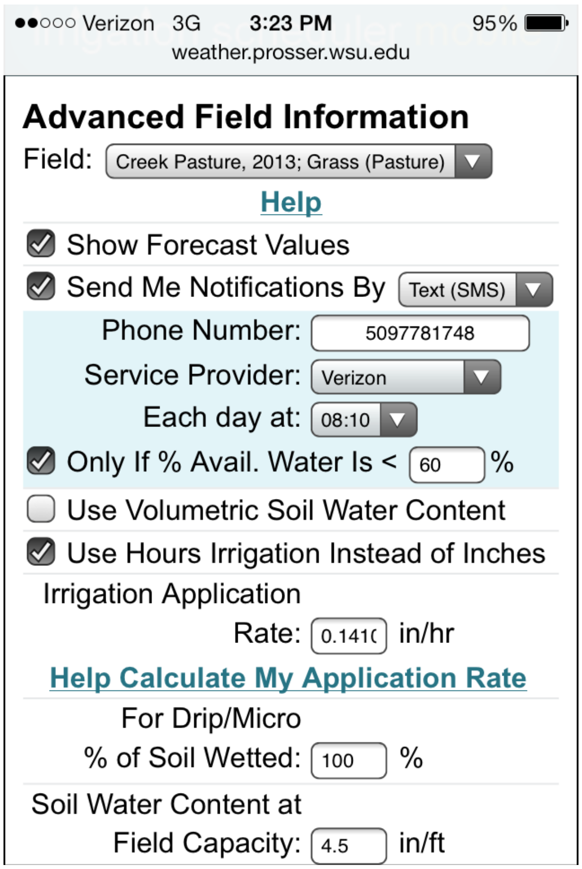
Send Me Notifications: Check this box to get email or text message notifications sent to you on the status of your field. If you choose to be notified by email you will be asked for your email address. If you choose to be notified by text (SMS) message you will be asked for your mobile phone number and your service provider. You can also choose what time of day the notification will be sent. You can also elect to only be notified when your percent of available soil water has been depleted to less than an entered threshold value. (See Figure 16)

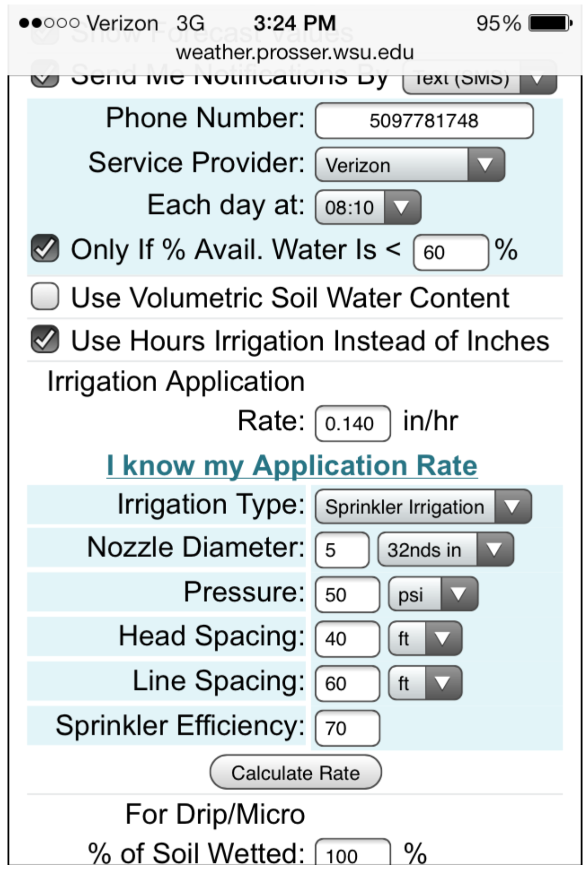
Use Hours Instead of Inches: Many irrigators think in terms of hours of irrigation run time instead of inches of water applied. Applied irrigation can be entered in hours, and the soil water deficit can be displayed in hours instead of inches. If you prefer to use hours an irrigation application rate in inches per hour must be provided. Calculators are available on this page to "Help Calculate My Application Rate" for drip, sprinkle, and general irrigation systems using a variety of different units. Reasonable assumptions of irrigation application efficiency are provided for each system. (See Figure 23)

Use Volumetric Soil Water Content: Most soil moisture sensors display volumetric soil water content (volume of water/volume of soil) instead of the percent of available water (which is easier to understand). If you would prefer to see and enter volumetric soil water content in the Daily Budget Table then check this box.

For Drip/Micro, % of Soil Wetted: In many perennial cropping systems under drip or micro irrigation, the entire soil volume is not used. For example a drip irrigation system in a wine grape vineyard may wet a 4 ft width of soil in an 8 ft row spacing. In this case only 50% of the soil is used to store water since the inter-rows remain dry. The soil's water holding capacity can be reduced by multiplying by this percentage to reflect this.

Soil Water Content at Field Capacity: This is the maximum amount of water that the soil can hold long term against gravity. After a soil is at the field capacity (Full point) adding more water will result in the water moving down through the soil profile and possibly past the bottom of the root zone (tracked on the "Deep Water Loss Chart"). Field Capacity is measured in inches of water per foot of soil depth.





Figures 22-23. Advanced Field Information Setup Screen

Soil Available Water Holding Capacity (AWC): This is field capacity minus wilting point, or the amount of water the soil can hold between full and empty. AWC times the soil depth gives the available water supply. The Empty/Dead (permanent wilting point) is calculated using this number and field capacity. Soil Available Water Holding Capacity is measured in inches of water per foot of soil depth.

Management Allowable Deficit (%): Abbreviated MAD, this is the percent depletion of the total available water below which the plant begins to experience water stress. *100% minus MAD is the First Water Stress point* as a percent of the available water holding capacity. As the soil dries down below this point the plant will experience increasing amounts of water stress until the plant will die when it reaches the Empty/Dead (permanent wilting) point. Daily crop water use estimates are proportionately decreased from the full value to zero as the soil water content decrease from MAD to the soil's permanent wilting point.

Planting/Emergence Date: Date the plant that the crop emerges and/or the plant starts using water. This is the start date for the soil water budget model. (See Figure 24.)

Crop Canopy Cover Exceeds 10% of Field: The date that crop water use starts increasing. (See Figure 24.)

Crop Canopy Exceeds 70% of Field (Full Cover) Date: The date that the crop canopy exceeds 70% - 80% of the field area or shades 70% - 80% of the ground area. At this point the crop coefficient reaches a maximum and stays at this maximum until the Initial Maturation Date (below). (See Figure 24.)

Crop Initial Maturation Date: After this date the crop begins to dry up, senesce or otherwise shut down and water use begins to decrease. (See Figure 24.)

End of Growing Season Date: Water use stops on this date. Often this coincides with harvest, or the first killing frost. This is the last date of the model. (See Figure 24.)

Root Depth on Start Date: The effects of a growing root depth is included in the soil water budget model. This is the root depth in inches on the starting or plant emergence date. (See Figure 24.)

Maximum Managed Root Zone Depth: This is the maximum root depth reached in the season. It is assumed that the plant root reaches this depth on the Crop Canopy Full Cover Date. (See Figure 24.)

Initial Crop Coefficient: The crop coefficient (Kc) from emergence to the 10% Cover date. (See Figure 24.) This Kc is based on alfalfa reference ETr.

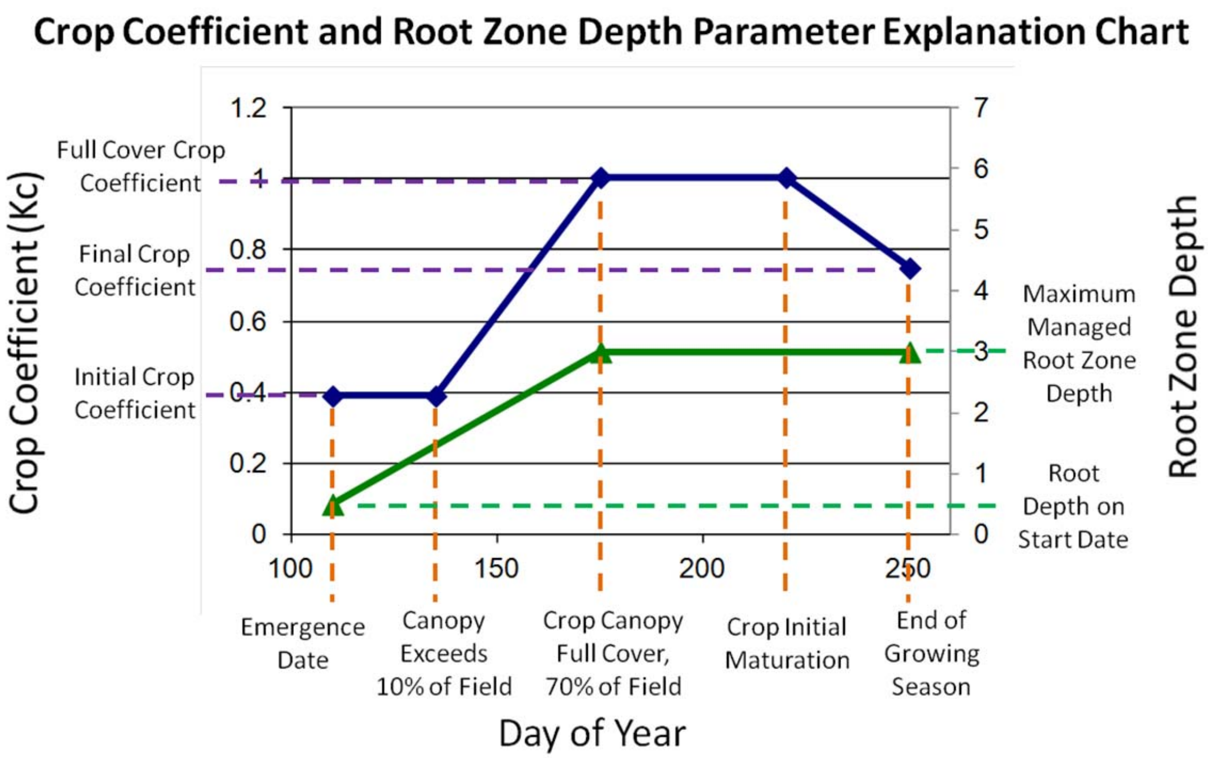


Figure 24. How crop coefficients and root growth are defined by the parameters in Field Settings.

Full Cover Crop Coefficient: The crop coefficient (Kc) at full cover. This is the peak, or maximum crop coefficient. (See Figure 24.) This Kc is based on alfalfa reference ETr.

Final Crop Coefficient: Crop coefficient (Kc) at the end of the season. (See Figure 24.) This Kc is based on alfalfa reference ETr.

Post Cutting Kc Flat Days: After cutting a forage, this is the number of days before regrowth starts.

Post Cutting Kc Recovery Days: After cutting a forage this is the number of days after regrowth starts for the forage to regrow to full cover again.

Add/Delete Fields

Selecting this menu brings up the screen in Figure 25. You can add a new field, or completely delete an existing field from this menu.

Add New Field: Use this to add a new field.

Delete Selected Field: Permanently removes the currently selected field and all of its settings and associated data.

Field Name: Use this to name the field.

Field Year: This is the growing year. If a previous year is selected, then that previous year's weather data will be used in the water budget. Use the current year for ongoing or current irrigation scheduling.

Network: Pick the agricultural weather network from your state that has the station that best represents your location. A list of agricultural weather networks whose data can be accessed by this irrigation scheduling tool are given in Table 1. Figure 30 is a map of these stations.

Table 1. Irrigation Scheduler Mobile currently can work with data from the following networks.

Network	States Served	Managed By	Website
AgWeatherNet	Washington	Washington State University	http://weather.wsu.edu/
CoAgMet	Colorado	Colorado State University	http://www.coagmet.colostate.edu/
AZMET	Arizona	University of Arizona	http://ag.arizona.edu/azmet/
NDAWN	North Dakota	North Dakota State University	http://ndawn.ndsu.nodak.edu/
ADAWN	South Dakota	South Dakota State University	http://climate.sdstate.edu/climate_site/ag_data.htm
CIMIS	California	California Dept. Water Resources	http://wwwcimis.water.ca.gov/cimis/welcome.jsp

AgriMet	WA, OR, ID, NV, MT	US Bureau of Reclamation, Pacific Northwest Region	http://www.usbr.gov/pn/agrimet/
AgriMet	MT	US Bureau of Reclamation, Great Plains Region	http://www.usbr.gov/gp/agrimet/

Weather Station: This tool automatically pulls the calculated daily reference evapotranspiration (ET) rates and measured precipitation from this station. Choose a station that best represents the weather conditions at your field.

Field Crop: Based on the selected crop, default growing season dates, crop coefficients, management allowable deficit (MAD) rates, and rooting depths are chosen. These crop parameters can be later edited in "Field Settings".

Field Soil: Based on the soil texture chosen, default field capacity, wilting point, and water holding capacity values are chosen. These soil parameters can be later edited in "Field Settings".

Forage Cuttings

Harvested forages such as alfalfa, grass hay, and sometimes mint can have multiple cuttings per season. After a forage crop is cut the crop coefficients are greatly decreased since the height and leaf area of the forage has been removed. The model knows which crops are forages and has default lag and recovery periods for these crops where the crop coefficients are temporarily reduced following a cutting (Appendix B). For these crops there will be an additional check box titled "Apply Forage Cutting Today" in the "Edit" expansion menu on the "Daily Budget Table". Checking this box on the day that the forage was cut will alter the crop coefficients during the recovery phase of the forage (Figure 25). It will also put a mark on the Soil Water Chart to indicate the forage cutting (Figure 26).

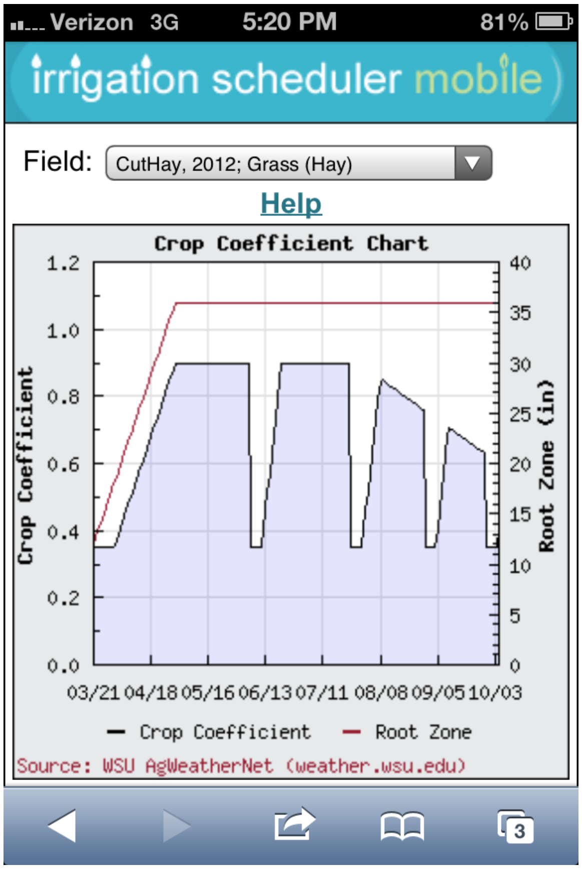


Figure 25. Crop Coeff. Chart showing cuttings.

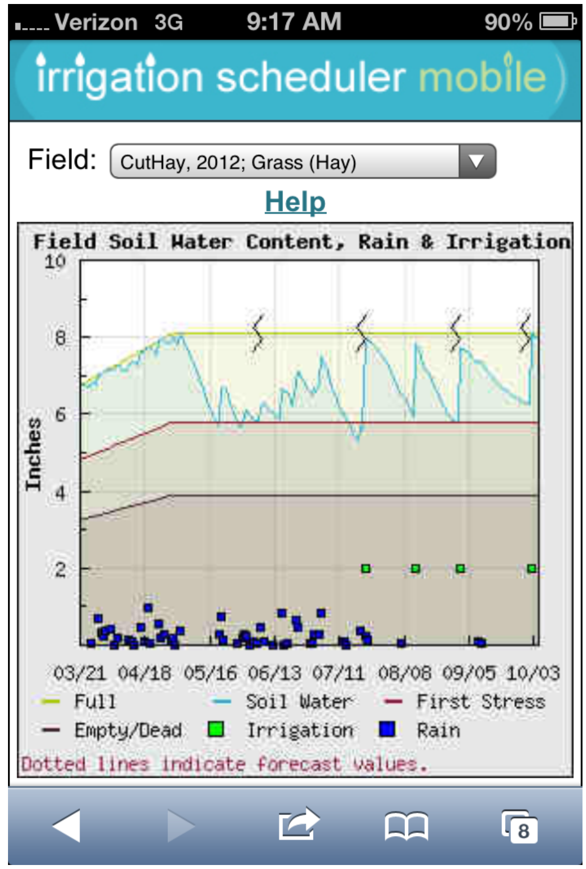


Figure 26. Cutting dates shown on the Soil Water Chart.

Full Size Screen Version

There is a version of this model that is set up for use on full-size computer screens at http://weather.wsu.edu (Figure 27). The operation of this is essentially identical to the mobile version, except that the charts are larger. Making changes to fields in this version will apply the changes to the mobile version and vise-versa.

Field Activity Reports: One feature that is available on the full size version that is not available on the mobile version is the option to show a report of your interaction with the Irrigation Scheduler. This was requested as a way to show certain agencies that you have been actively using the model for irrigation scheduling so that they will feel that incentives for irrigation scheduling are well spent.

The model counts the number of days that you view or edit that field in a month (Figure 28). Views or Edits are counted whether you use the full-page or small screen (mobile) version. Loading any page for the field is counted as a view. Making an edit in the Daily Budget Table (such as adding an irrigation event), or in the Field Settings is counted as an edit.

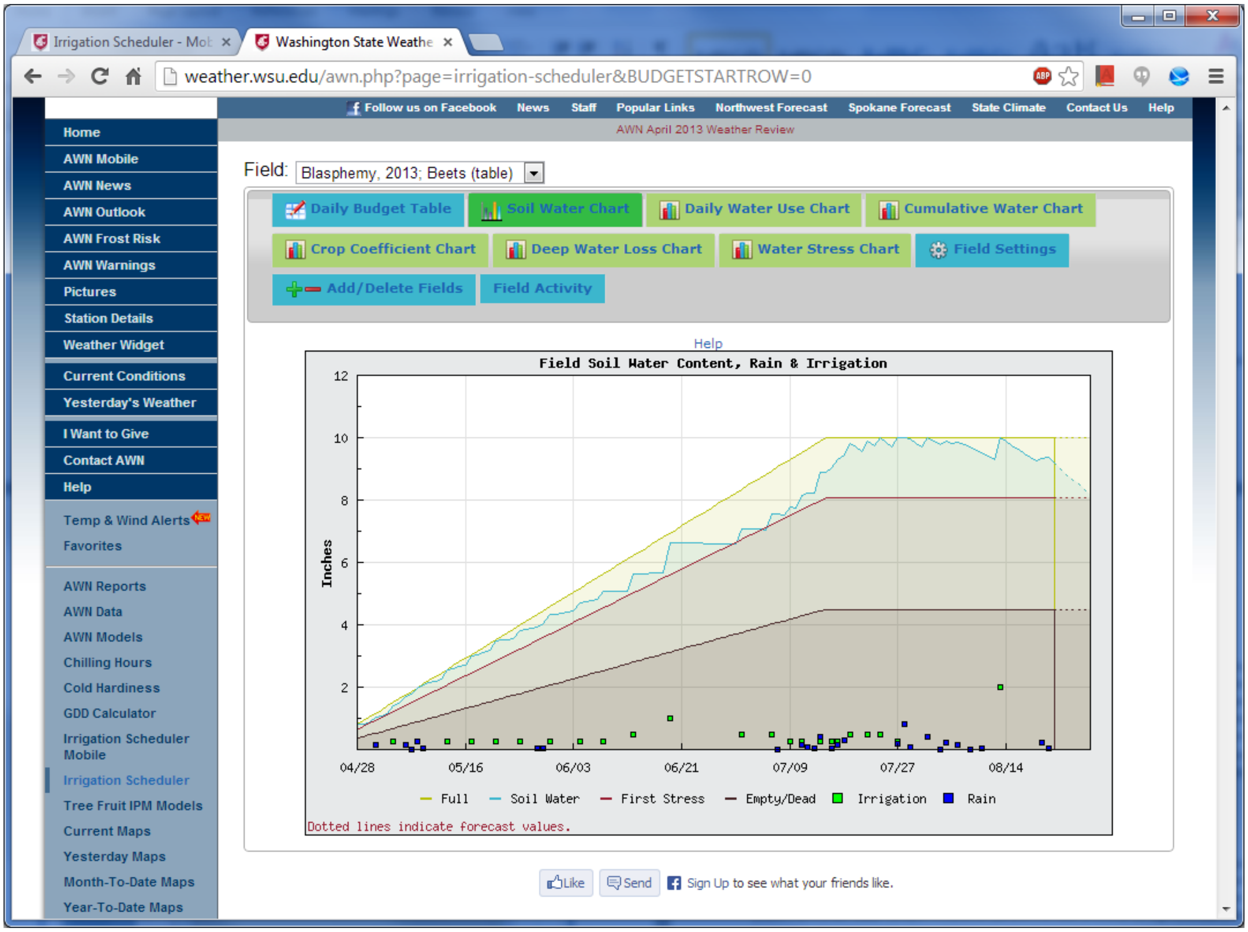


Figure 27. Full Screen version.

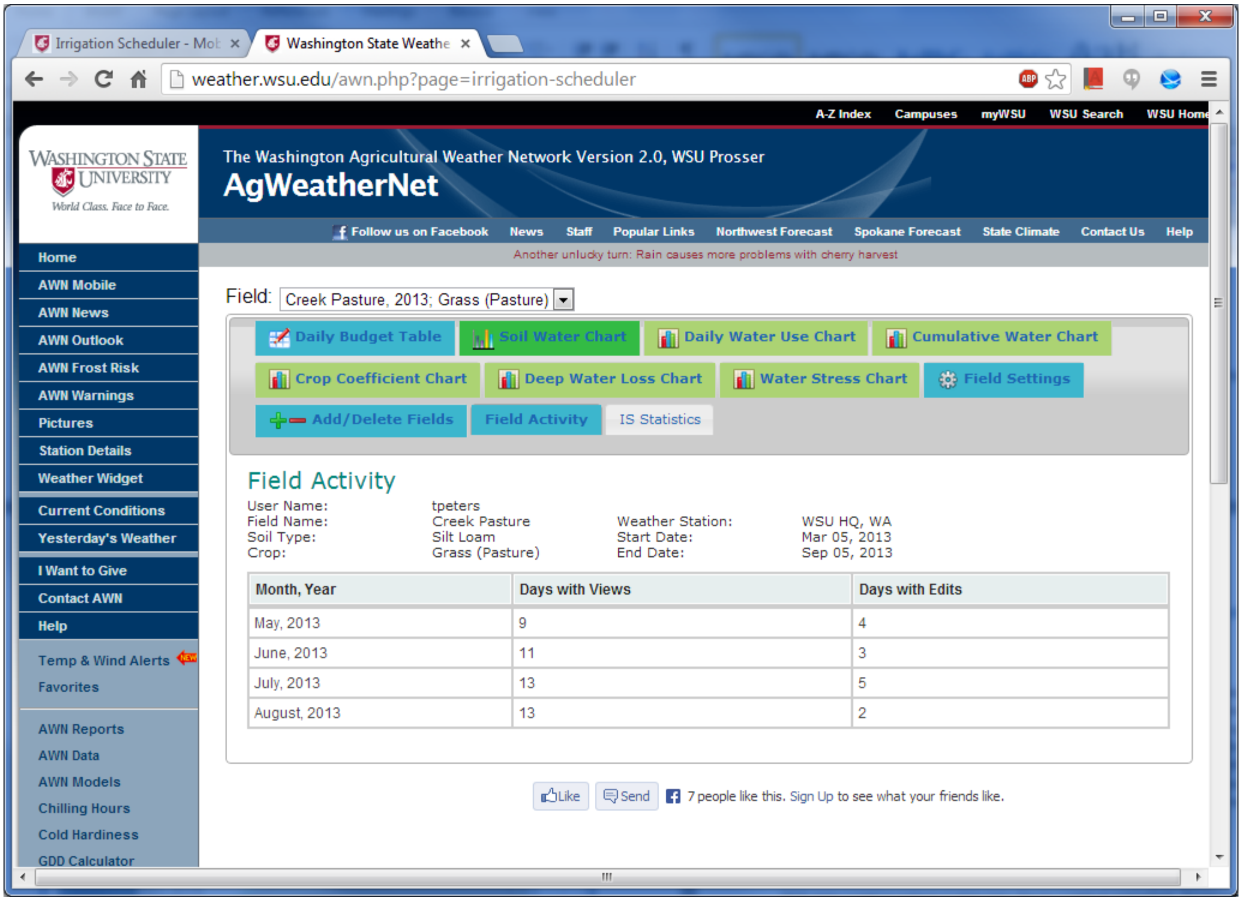


Figure 28. Field Activity report that is available from the full-screen version.

Suggestions for Different Irrigation/Cropping Systems

Rill or Furrow Irrigation: With surface irrigation methods it is difficult to know exactly how much water infiltrated into the soil. A good assumption is that at each irrigation event you completely refill the soil water deficit to field capacity in the entire root zone. Simulate this by entering a large number at each irrigation event (like 3-4 inches), entering a number equivalent to the soil water deficit, or resetting the Percent Available Water number to 100% at each irrigation event.

The model is useful with surface irrigation in that it will indicate when the soil is getting dry again and when to irrigate. To be the most efficient with your water resources, wait to irrigate when the soil water content is near the First Stress (MAD) line. Often growers learn they can wait a little longer than they thought before irrigating again and they end up saving an irrigation or two over the season.

Moving Irrigation Sets: With many irrigation systems it takes many days to irrigate an entire field. This brings up the question, “Which date should I put the irrigation on?” Simply choose one part of the field and throughout the whole season enter the irrigation on the date that that part of the field receives irrigation water. Be aware that the soil water content in the other parts of the field will either be slightly ahead or behind the model. It might be easier if you choose a location that is easier to remember when it was irrigated, such as the first set. If correlating/correcting with soil moisture measurements, be sure to choose the part of the field where the measurements are being taken.

Use with Soil Water Content Sensors: Updating the model with periodic soil moisture measurements will greatly improve the accuracy of the soil moisture estimate. These can be used to fine-tune the model as well. For example, if you find that the soil moisture measurement is consistently higher than that estimated, then the model is over-estimating crop water use and the crop coefficients should be adjusted down for that time period. Be aware that soil moisture measurements are quite variable and may be high one time then low the next. Use seasonal trends and your good judgment to adjust the model.

Most soil water content sensors provide in the number as a volumetric soil water content (% water of total soil volume) this number is available by clicking the date in the Daily Budget table for expanded information (Figure 13).

Use with Soil Water Tension Sensors: Tensiometers and Granular Matrix (Watermark) sensors don’t measure soil water content and therefore it is very difficult (although not impossible) to compare the measurements directly with the model. However, these sensors should indicate that the soil is drier (greater soil water tension) as the soil water content approaches and goes below the MAD line. For additional help see the publication “Practical Use of Soil Moisture Sensors for Irrigation Scheduling” by Troy Peters.

The Effects of Irrigation Frequency. With center pivots and some solid-set irrigation systems water is applied much more frequently than other irrigation systems such as surface (rill) or hand-lines and wheel-lines. High frequency irrigations mean that the soil surface and plant leaves are wet a greater percentage of the time and therefore a greater amount of water is lost to evaporation. In other words, the crop uses/needs more water. Because of this, you might need to adjust the crop coefficients *up* 5-10% in Field Settings to compensate for this.

Deliberate Water Stress: With some crops, such as wine grapes, it is desirable to deliberately cause water stress to get the desired crop quality results. Recall that the plant will see approximately linearly increasing water stress from barely any at the red, First Stress (MAD) line to maximum stress at the black, Empty/Dead (Permanent Wilting Point) line (see Figure 5). Deliberately causing stress is done by purposefully allowing the soil water to dry down below the First Stress line (Figure 29).

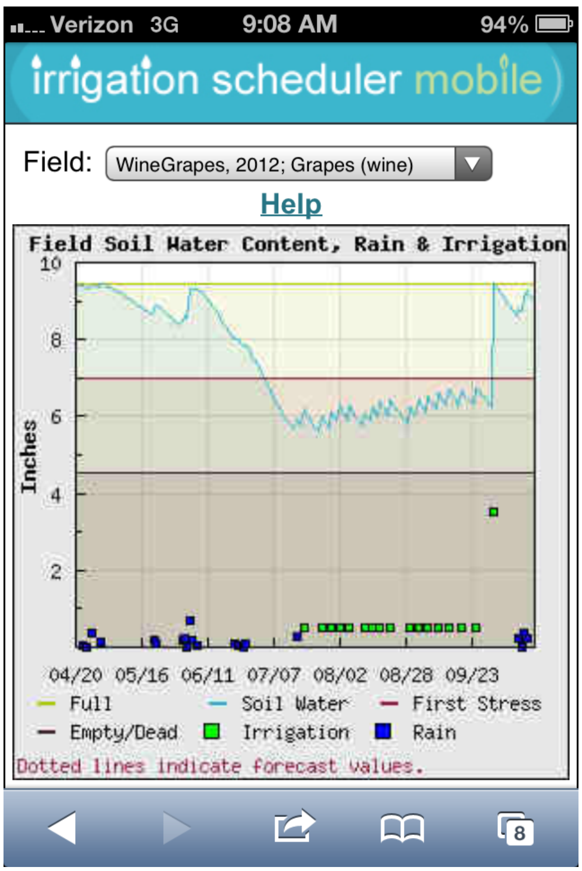


Figure 29. Water stressing wine grapes. Irrigation after harvest was done to restore the health of the vines.

Technical Details on Adapting the Model to Your Area

This model was set up to be used outside of just Washington State. It was written in PHP and MySQL, both of which are free, open-source applications that run on a web server. The code is freely available under an open source, GPL license if someone wants to set it up to run on a different server. It is permissible to re-brand it as long as the developers are acknowledged and it is freely available to users.

Other Weather Networks: It can easily accept rainfall and weather data for evapotranspiration calculations from any weather network whose data can be accessed over the internet (Table 1). Additional states or networks can be fairly easily added if there is an automated way to get access to up-to-date historical weather data. Please contact us (troy_peters@wsu.edu) to add your network. It should also work well with international data networks.

Alternative Crops and Crop Defaults: Unfortunately crop coefficients are not always accurately transferrable from one climatological region to another. Also the growing season dates used as defaults in the model obviously vary with different climates. To account for this Irrigation Scheduler Mobile can accept different default crop coefficients and season growth dates that are attached to administrator-defined groups of weather stations. For example, the model is now set up so that when a grower chooses a weather station in Western Washington (the evergreen side) it will use different crop coefficients than if a weather station in Eastern Washington (the ever-brown side) is chosen. Different states can also have their own set of default crops, crop coefficients, and growth season dates. Please contact Troy Peters (troy_peters@wsu.edu) for more information on how to get these made specific to your state or growing area. This only affects the default crop values automatically populated when a grower sets up a new field.

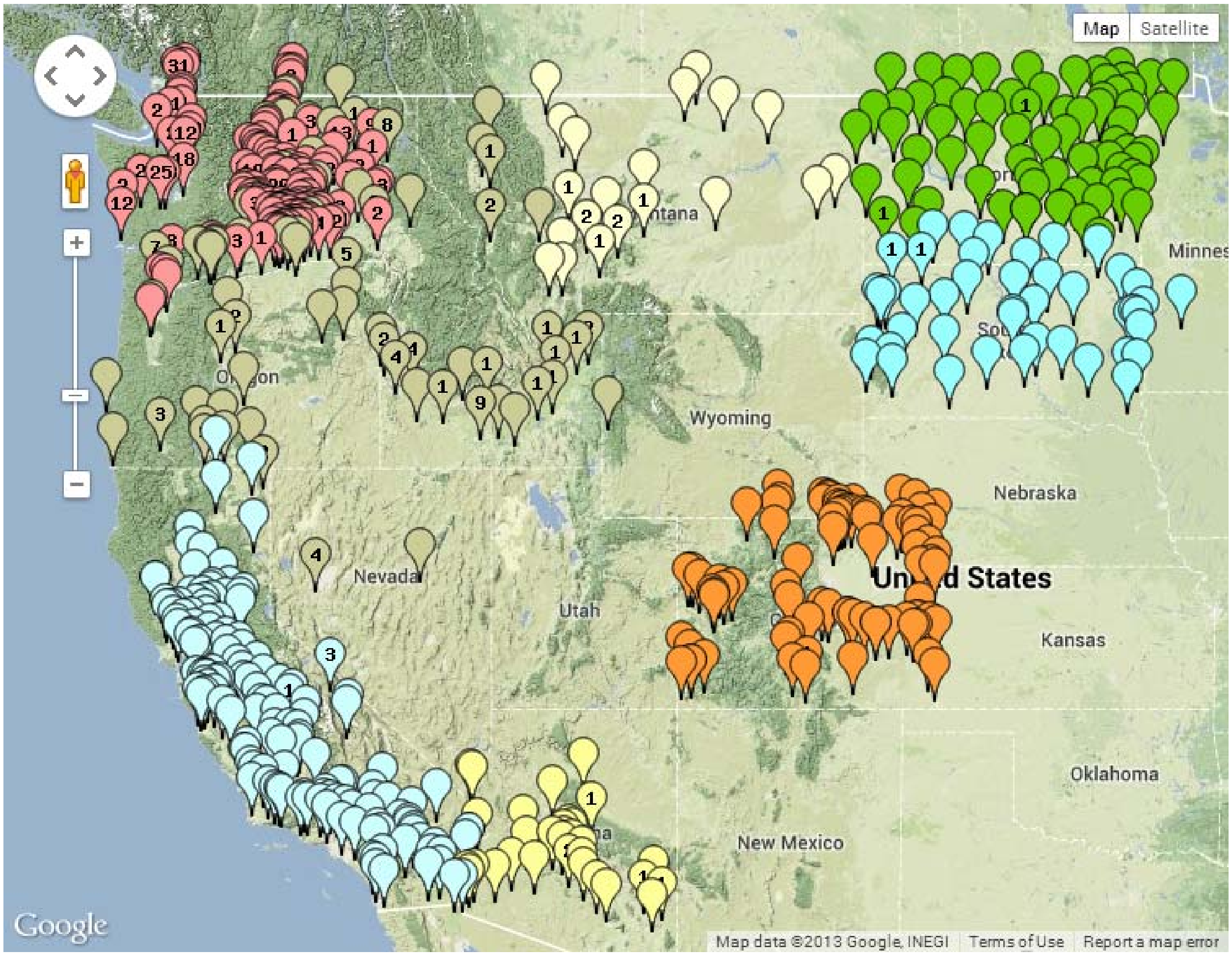


Figure 30. A map of the stations and weather networks that Irrigation Scheduler Mobile currently works with (as of Oct. 1, 2013). See Table 1 for additional details. The numbers in the balloon markers are the current number of fields set up using that station.

Conclusion

Irrigation Scheduler Mobile is a free, easy to use, and flexible irrigation scheduling tool that can be used from any smart phone or any web browser. It is simple to use and flexible. It also can work with any weather data that can be automatically accessed over the internet.

Acknowledgements

Sean Hill was the primary developer of Irrigation Scheduler Mobile. He is a very bright, capable developer who conceived many of the concepts used in this program. He deserves the lion's share of the credit for making this happen. He is a web developer for AgWeatherNet. Funding for Sean's time was graciously provided by the director of AgWeatherNet; Gerrit Hoogenboom. Additional funding for prior development by Cynthia Tiawana was provided by the USDA Water Quality Research Initiative. The American Society of Agricultural and Biological Engineers is also providing funding for additional development and to turn this into a downloadable smart phone app. Thank you!

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Appendix A: Defaults by Soil Texture. All units are in inches of water per foot of soil depth. More accurate estimates for your particular soil are available from the NRCS Web Soil Survey (http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm)

	Soil Water Content (in/ft)		
Soil Texture	Field Capacity	Wilting Point	AWC
Coarse Sand	1.2	0.6	0.7
Fine Sand	1.5	0.7	0.8
Loamy Sand	2.2	1.2	1.0
Sandy Loam	2.7	1.3	1.4
Fine Sandy Loam	3.4	1.6	1.8
Sandy Clay Loam	4.0	2.0	2.0
Loam	4.0	1.8	2.2
Silt Loam	4.3	2.0	2.3
Silty Clay Loam	4.6	2.8	1.8
Clay Loam	4.8	3.0	1.8
Silty Clay	4.8	3.2	1.6
Clay	4.8	3.4	1.4
Peat Mucks	5.0	2.6	2.4

Appendix B: Crop defaults used. These can be customized to weather networks, or even groups of weather stations within a network.

Crop Name	Crop Development Dates for Crop Coefficient Curve (DOY)					Crop Coefficients			Root Depths (ft)		MAD %
	Planting/ Emergence	> 10% of Field	Full Cover/ > 70%	Initial Maturation	End of Season	Initial	Full Cover	Final	Starting	Max.	
Alfalfa *	91	100	122	139	278	0.33	1.07	0.95	4.0	5.0	55
Apples	100	112	149	240	290	0.39	1.05	0.50	3.5	3.5	50
Apricots	100	112	149	220	278	0.39	1.10	0.50	3.5	3.5	50
Asparagus	120	130	214	260	278	0.36	1.00	0.87	3.5	5.0	55
Beans (dry)	146	156	191	211	242	0.25	0.95	0.30	0.4	2.5	50
Beans (green)	146	150	180	200	211	0.25	0.95	0.80	0.4	2.5	40
Beets (table)	117	135	195	239	276	0.40	0.88	0.79	0.2	2.5	35
Blackberries	90	95	145	190	280	0.25	1.05	0.70	3.5	4.0	50
Blueberries	85	90	111	195	225	0.25	1.03	0.90	3.0	4.0	50
Bluegrass Seed	72	80	126	155	192	0.25	0.95	0.25	1.0	2.5	50
Broccoli	91	119	160	218	243	0.50	0.87	0.80	0.2	2.0	35
Brussel Sprouts	91	119	160	218	243	0.58	0.88	0.79	0.2	2.0	35
Cabbage	91	92	160	185	243	0.25	1.00	0.25	0.5	2.0	40
Canola	76	83	122	164	183	0.20	1.05	0.30	0.5	4.0	55
Cantaloupe	136	153	195	229	243	0.42	0.71	0.50	0.5	3.0	50
Carrots	91	119	160	220	243	0.70	0.85	0.75	0.2	2.0	35
Cauliflower	91	119	160	218	243	0.58	0.87	0.79	0.2	2.0	35
Celery	127	140	186	220	253	0.65	0.80	0.80	0.2	1.5	40
Cheatgrass	60	62	83	104	130	0.25	0.80	0.25	0.5	2.5	65
Cherries	110	112	141	220	278	0.39	1.12	0.50	3.5	3.5	50
Clover *	91	95	117	244	278	0.33	0.92	0.75	2.0	2.5	45
Corn (grain)	129	151	201	236	259	0.25	1.00	0.75	0.4	3.5	50
Corn (sweet)	130	152	203	230	240	0.25	1.00	0.86	0.4	2.5	40
Cranberries	105	106	121	277	278	0.33	0.75	0.42	0.2	0.3	40
Cucumbers	136	140	174	240	278	0.50	0.70	0.70	0.5	2.5	40
Garlic	91	119	160	218	243	0.58	0.83	0.57	0.5	1.5	30

Appendix B: Crop Defaults Used in the Model, Continued.

Crop Name	Crop Development Dates for Crop Coefficient Curve (DOY)					Crop Coefficients			Root Depths (ft)		MAD %
	Planting/ Emergence	> 10% of Field	Full Cover/ > 70%	Initial Maturation	End of Season	Initial	Full Cover	Final	Starting	Max.	
Grain (Spring)	92	100	160	195	213	0.25	1.05	0.70	0.3	3.5	50
Grain (Winter)	66	85	128	184	196	0.25	1.05	0.90	1.0	3.5	50
Grapes (juice)	110	114	180	277	278	0.25	0.90	0.75	3.0	3.0	40
Grapes (wine)	110	135	210	277	278	0.15	0.70	0.70	3.0	5.0	65
Grass (Hay) **	80	90	120	209	278	0.50	0.90	0.72	1.0	3.0	55
Grass (Pasture)	80	87	118	244	278	0.25	0.65	0.50	2.0	3.0	55
Grass (Tall Pasture)	80	87	118	244	278	0.25	0.80	0.50	2.0	3.0	55
Grass (Turf)	72	80	108	244	278	0.80	0.80	0.80	1.0	1.5	50
Hops	110	158	230	250	274	0.25	1.05	0.20	3.0	4.0	50
Lentils	105	115	155	182	215	0.25	1.02	0.30	0.5	2.5	50
Lettuce	95	96	110	123	125	0.58	0.83	0.79	0.2	1.5	25
Melons	136	140	174	240	278	0.25	0.80	0.60	0.5	2.5	40
Mustard	76	83	122	164	183	0.25	0.85	0.30	0.5	2.0	55
Onions (dry)	90	122	162	212	239	0.50	1.07	0.50	0.2	1.5	35
Onions (green)	74	99	129	139	144	0.50	1.00	1.00	0.5	1.5	35
Peaches	110	112	145	220	278	0.39	1.12	0.50	3.5	3.5	50
Pears	110	112	149	226	278	0.39	1.15	0.50	3.5	3.5	50
Peas	90	97	163	174	198	0.30	1.00	0.50	0.5	2.5	40
Peppermint *	86	93	156	270	278	0.25	0.98	0.85	1.5	2.0	40
Peppers	136	153	195	232	243	0.50	0.85	0.71	0.5	2.0	35
Plums	110	112	149	239	278	0.20	1.05	0.50	3.5	3.5	50
Potatoes	127	140	186	220	253	0.40	0.85	0.60	1.0	2.0	35
Pumpkin	136	161	212	250	278	0.42	0.83	0.67	0.5	3.0	45
Radishes	95	96	110	123	125	0.53	0.72	0.67	0.5	1.0	40
Raspberries	90	95	144	227	278	0.20	1.08	0.70	3.5	4.0	50

Appendix B: Crop Defaults Used in the Model, Continued.

	Crop Development Dates for Crop Coefficient Curve (DOY)					Crop Coefficients			Root Depths (ft)		
Crop Name	Planting/ Emergence	> 10% of Field	Full Cover/ > 70%	Initial Maturation	End of Season	Initial	Full Cover	Final	Starting	Max.	MAD %
Safflower	90	98	143	193	220	0.20	1.08	0.25	0.5	5.0	55
Sorghum	130	150	185	230	260	0.25	0.90	0.85	0.5	2.0	55
Soybeans	121	140	175	235	260	0.36	0.96	0.30	0.5	3.0	55
Spearmint *	110	124	165	212	243	0.25	1.03	0.80	1.5	2.0	40
Spinach	88	120	168	206	215	0.55	0.80	0.75	0.5	1.5	25
Squash	136	161	212	250	278	0.40	0.80	0.60	0.5	3.5	50
Strawberries	80	93	164	207	278	0.33	0.70	0.55	1.0	1.5	30
Sugar beets	117	135	195	239	276	0.25	1.05	0.70	0.5	4.5	50
Sunflowers	105	130	165	210	234	0.25	0.92	0.29	0.5	4.5	65
Tomatoes	136	153	195	229	243	0.50	0.95	0.70	0.5	3.0	40
Tubers	80	93	164	207	278	0.42	0.92	0.79	0.5	3.5	40
Watermelon	105	130	165	210	234	0.33	0.85	0.85	0.5	3.5	50

* Default post-cutting lag and recovery time periods are 7 and 14 days respectively.

** Default post-cutting lag and recovery time periods are 5 and 10 days respectively.

Rapid Implementation Program (RIP) to Improve Operational Management and Efficiencies in Irrigation Districts

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Abstract. *The Rapid Intervention Program (RIP) was developed over a ten year period by the Texas Agricultural Extension Service, and is a structured and systematic approach for analyzing the distribution network and on-farm irrigation of irrigation schemes, and developing recommendations on improved management strategies. We applied the RIP in several irrigation districts in US and oversea, and to an irrigation division of the Lower Colorado River Authority in Texas.*

RIP is designed as a low-cost, user-friendly and versatile approach that takes advantage of the knowledge and experience of the scheme operators and managers, and involves the combination in one single tool of several rating forms that were developed and applied in Texas. A key component is the training of operators, so that they could implement and transfer the RIP to other irrigation schemes. In this paper we will present the RIP components, the procedure of applying and adapting it to different districts, and some of the main results.

Keywords. Irrigation District, Water Management, Water Supply, Seepage, Irrigation Scheduling, GIS

INTRODUCTION

Irrigation schemes (or irrigation districts) throughout the world are faced with huge challenges as government support for maintenance and modernizations have been reduced. Many irrigation schemes are self-funded through a fee collection that typically is insufficient to cover operating expenses alone. In addition, many irrigation schemes are facing increases in water competition and decreases in water supplies, and often aging and inefficient water distribution systems.

The Rapid Intervention Program (RIP) was developed over a ten year period by the Texas A&M Extension Service, under the direction of Guy Fipps (Bonaiti and Fipps, 2012, Bonaiti and Fipps, 2013a). RIP is a structured and systematic approach for analyzing the distribution network and on-farm irrigation of irrigation schemes, and developing recommendations on improved management strategies. RIP is designed as a low-cost, user-friendly and versatile approach that takes advantage of the knowledge and experience of the scheme operators and managers.

Components include:

- Inventory of basic data needed to estimate water supply, flows and on-farm irrigation needs.
- Distribution Network Hydraulic Head Survey and Analysis Tool.
- Distribution Network Condition Rating Tool.
- On-farm Head Survey and Analysis Tool.
- Spreadsheets for storage and analysis of data.
- GIS map of the command area.
- Training curriculums for persons implementing the RIP in flow measurement, canal management and basic concepts of surface irrigation.

A key component of the RIP is the training of collaborators so that they can implement and transfer the RIP to other irrigation schemes. Training is provided also on basic concepts of flow measurement and canal management, and on Excel and ArcGIS for Desktop software. All material is collected into a RIP Manual, to serve as both a training program and a reference guide to all the steps required in order to successfully apply the RIP.

The objectives of this paper is to describe how we designed a RIP procedure for irrigation schemes in Iraq, and the main components of the RIP manual which is designed to help trained operators to apply it successfully. For this study we selected irrigation schemes which are representative of the conditions in the Center and South of Iraq.

In this paper we also present results of a study conducted in the Gulf Coast Irrigation Division of the Lower Colorado River Authority (LCRA) in Texas, where we further developed the RIP with an emphasis on the prioritization of canals for lining (Bonaiti and Fipps, 2013b).

RIP MANUAL AND GENERAL PROCEDURE

The RIP manual (Manual) is organized to serve as both a training program and a reference guide to all the steps required in order to successfully apply the RIP. Each of the four major RIP components is discussed in the Manual along with comments and/or observations that the users may find useful. The Manual also includes Appendices which provide:

- A copy of all forms in English and Arabic.
- The suggested training curriculum for the specialized skills needed related to GIS mapping, use of spreadsheets and flow measurement.
- Examples of case studies of the application of the RIP to irrigation schemes in Iraq.

The Survey and Data Collection Tools were applied according to the following general steps:

1. Map the irrigation scheme with GIS. A map with details on canals and irrigated areas is a critical part of the RIP and is used to help organize and analyze the data collected. Usually, any existing maps are used along with recent aerial photographs to create the GIS. The GIS serves as a reference when discussing the data collection forms with the operators.

2. Completion of all forms. Typically, this is done in three stages:

    a. First in the office with assistance of the interviewers using the GIS as a reference, based on the operators' knowledge.

    b. Then the operators are instructed to go to the field and verify the information.

    c. The interviewers meet with the operators to verify all information.

3. Flow measurements. Actual flow rates required for all canal categories and at the on-farm turnout. Calculated flows based on the original design specifications are not useful for this purpose.

4. Enter data into RIP spreadsheets (Excel) and link to GIS as appropriate.

5. Analysis and Recommendations. The exact types of analyses that are done will vary from irrigation project to irrigation project due to their differences; thus, some of the spreadsheets and procedures will need to be modified depending on the specific conditions and objectives.

RIP assumes that the persons implementing the program have already had training and basic skills on use of GIS and Excel. However, implementers will need training to review basic concepts, and on how to apply these tools to the RIP. For example, Excel training covers how to use the RIP spreadsheets which are included on the Manual.

Persons who will conduct the flow measurements will need at least some understanding of open channel flow principle. Ideally, they will also have had experience with field instrumentation. Training is usually required on use of portable velocity meters. Even with experienced persons, training will help speeding up the field work and improve accuracy of measurement. Furthermore, speed up of measurement is particularly important when the water level in the canal fluctuates. Other devices, such as portable acoustic meters and flumes may also be used, but are not included in this manual.

SURVEYS

Distribution Network Hydraulic Head Survey and Analysis Tool (Head Survey)

The purpose of the Head Survey is the identification of areas and canals that currently have continuous or intermittent water supply problems, and the identification of the potential causes of these problems. The tools utilized for this survey are Head Survey Rating Forms, and Head Survey Spreadsheets. The Head Survey includes two sections, Head Problem and Drainage Problem.

We applied the survey as follows:

1. Obtain map (scale 1:25,000 or larger) of the distribution network and irrigated areas, making sure to identify for each canal the corresponding irrigated areas.

2. Working with the operators, complete survey forms for canals and command areas, and modify forms as needed:

    a. Train collaborators on how to rate canals and irrigated areas.

    b. Make changes in rating criteria and scale as needed.

    c. Identify canals and irrigated areas to be rated, and assign rating ID.

    d. Jointly complete survey.

3. Encourage operators to conduct ground truth.

4. Enter data into spreadsheet:

    a. Train collaborators on data entry (Excel spreadsheets).

    b. Enter data.

5. Analyze data and create maps showing results:

    a. Perform data quality control.

    b. Link data to GIS.

    c. Carry out additional analysis as needed.

    d. Review results with operators.

6. Create reports to include the following:

    a. Tables of results.

    b. GIS maps with results of rating for canals and irrigated areas.

Comments are included in the manual in order to help the user to avoid common mistakes and/or to plan future improvements. For example, with this rating it can happen that the same canal is rated differently when it serves areas that are rated differently. As two records for the same canal ID cannot be joined to the canal shape file but only related, these results cannot be displayed on map but only on tables.

An example of results of the Head Problem Survey application is reported below. Codes are entered in the forms, each of them representing a complete answer. Columns A1, A2, B and C in Table 1 represent the questions “Frequency of head problem during peak period”, “Frequency of head problem during non-peak period”, “Cause of head problem”, and “Severity of head problem” respectively. Figures 1 and 2 show the case of question A1, for which there are four possible answers: Never (0), Sometimes (1), Often (2), Always (3). Figure 3 shows the case of question C, for which there are three possible answers: Minor (0), Moderate (1), Major (2).

Table 1. Example of Head survey data summary in the Iraq case study ("n.d." for canals and command areas with no head problems)

HEAD PROBLEM						
Area_ID	Canal_ID	A1	A2	B	C	Notes
B-0/R	B-0/R	n.d.	n.d.	n.d.	n.d.	
B-0_I	B-0_I	n.d.	n.d.	n.d.	n.d.	
B-0_II	B-0_II	3	3	1, 2, 3d	1	
B-1	B-1	n.d.	n.d.	n.d.	n.d.	
B-2_I	B-2_I	n.d.	n.d.	n.d.	n.d.	
B-2_II	B-2_II	3	0	1, 2, 3d	0	
B-2_III	B-2_III	2	1	1, 2, 3d	1	
B-3	B-3	n.d.	n.d.	n.d.	n.d.	
B-4	B-4	n.d.	n.d.	n.d.	n.d.	
C-1_I	C-1_I	n.d.	n.d.	n.d.	n.d.	
C-1_II	C-1_II	3	2	3e, 3f	2	
C-3_I	C-3_I	n.d.	n.d.	n.d.	n.d.	
C-3_II	C-3_II	3	3	3e, 3f	1	
C-5_I	C-5_I	n.d.	n.d.	n.d.	n.d.	
C-5_II	C-5_II	3	2	3e, 3f	1	
BC-3	BC-3	n.d.	n.d.	n.d.	n.d.	
BC-4	BC-4	n.d.	n.d.	n.d.	n.d.	
BC-5	BC-5	n.d.	n.d.	n.d.	n.d.	
BC-6	BC-6	n.d.	n.d.	n.d.	n.d.	
BC-7_I	BC-7_I	n.d.	n.d.	n.d.	n.d.	
BC-7_II	BC-7_II	1	0	3d, 3f	0	
BC-8	BC-8	n.d.	n.d.	n.d.	n.d.	
BC-9	BC-9	n.d.	n.d.	n.d.	n.d.	
BC-9A	BC-9A	n.d.	n.d.	n.d.	n.d.	
BC-11	BC-11	n.d.	n.d.	n.d.	n.d.	
BC-12	BC-12	n.d.	n.d.	n.d.	n.d.	
BC-10_II	BC-10_II	3	3	3b, 3c, 3d, 3f	2	
BC-10_I	BC-10_II	n.d.	n.d.	n.d.	n.d.	
BC-10/13	BC-10/13	3	3	3c, 3d, 3f	2	
BC-19	BC-19	n.d.	n.d.	n.d.	n.d.	
BC-20/1	BC-20/1	n.d.	n.d.	n.d.	n.d.	
BC-20/2	BC-20/2	3	3	3b, 3d, 3f	0	
BC-20/2/2	BC-20/2/2	3	3	3b, 3d, 3f	0	
BC-18	BC-18	3	3	3b, 3d, 3f	0	

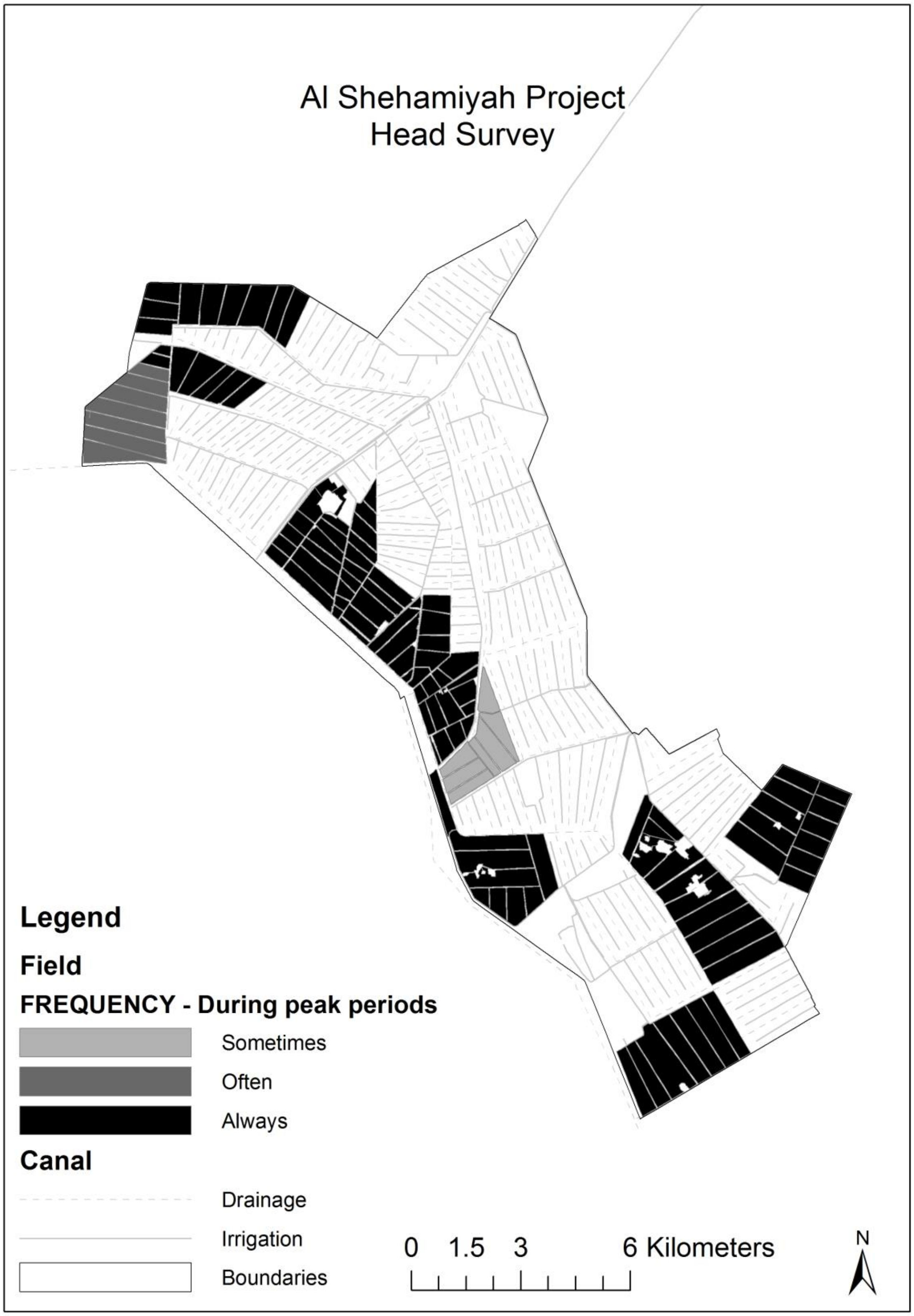

Figure 1. Example result for the Head Survey in the Iraq case study: Frequency during peak periods (Irrigated area)

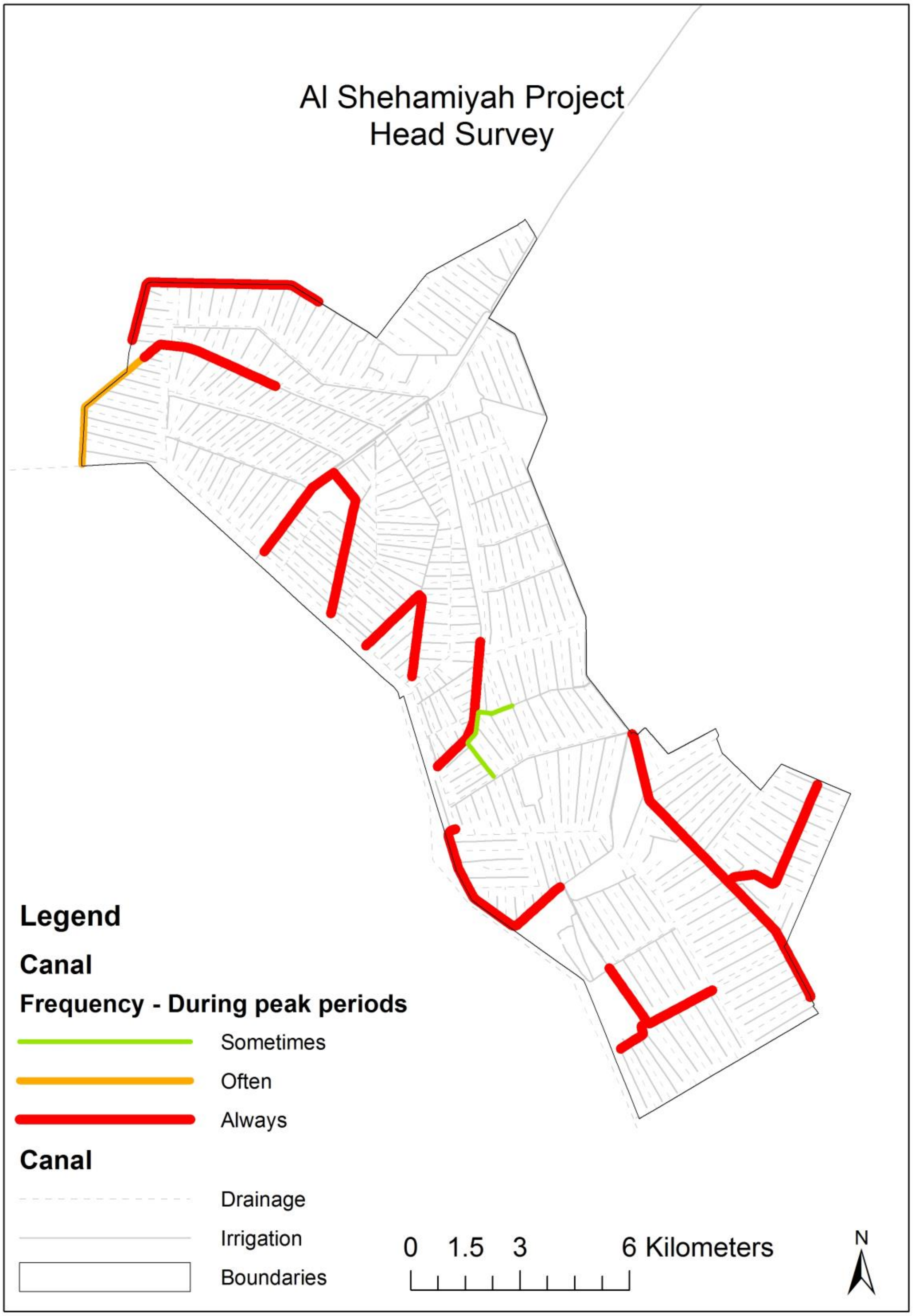

Figure 2. Example result for the Head Survey in the Iraq case study: Frequency during peak periods (Network)

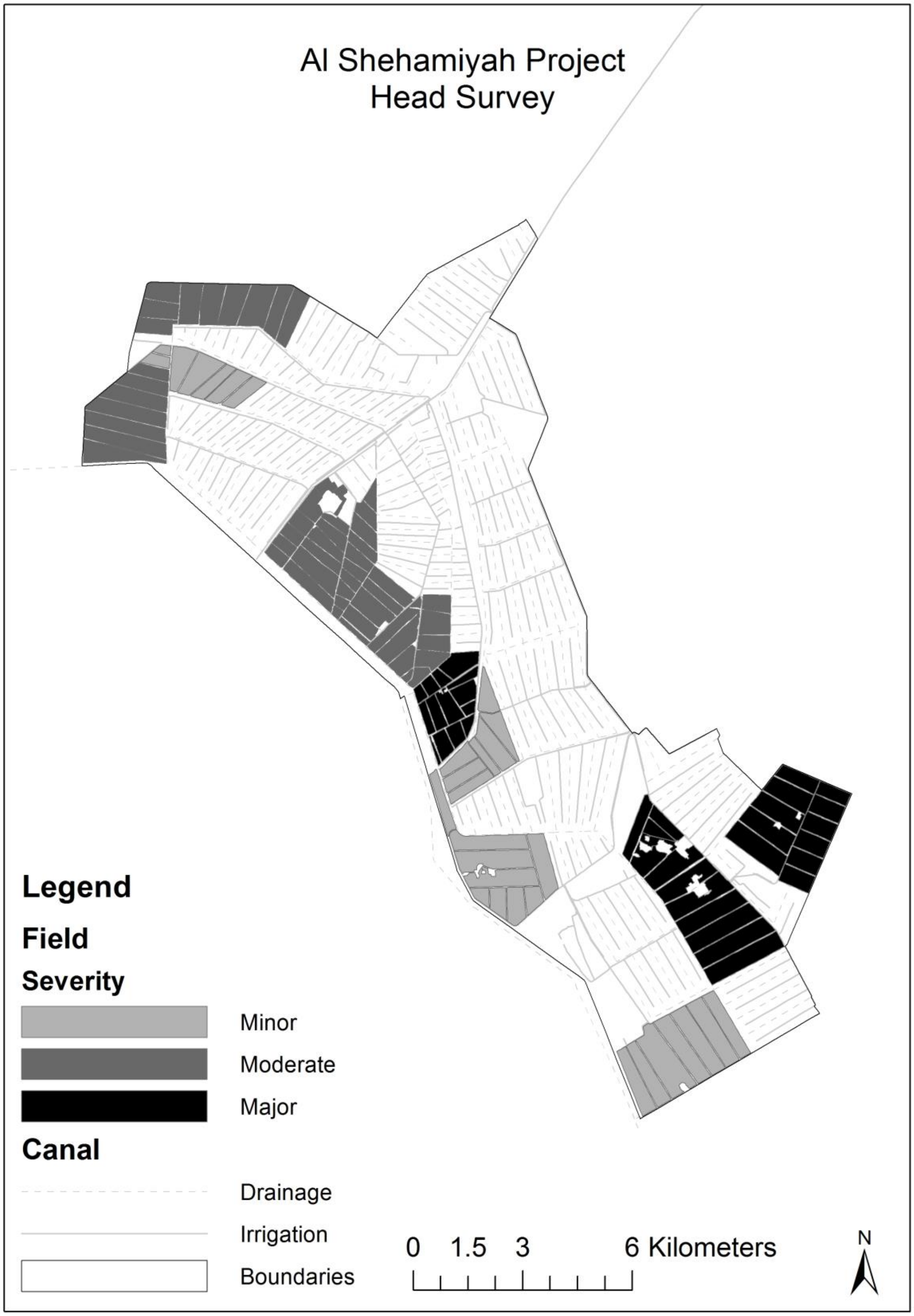

Figure 3. Example result for the Head Survey in the Iraq case study: Severity of head problem (Irrigated area)

Distribution Network Condition Rating Tool (Canal and Gate Evaluation)

The purpose of the Canal and Gate Evaluation is to assess general condition of the irrigation distribution network through a visual rating system to identify segments which need rehabilitation. The tools utilized for this survey are Distribution Network Condition Rating Form/Survey, and Excel Spreadsheet. The Canal and Gate Evaluation includes three sections, General Description, Questions to the Canal Riders, and Field Rating Forms (Concrete Canal, Earthen Canal, Gates).

As for the Head Survey, the Manual reports a suggested procedure and additional comments. For example we recommend to identify segments to be rated using existing hydraulic structures (such as diversion gates, control gates, bridges), and to make sure that segments are fairly homogeneous. For example, a segment will be split in more segments if during the field survey it results having a not homogeneous rating. An example of results of the application of the Concrete Canal Evaluation is reported in Table 2 and Figure 4. In figure we show the rating for the general conditions, i.e. column 10 in the table (0 = Excellent, 1 = Good, 2 = Fair, 3 = Poor, 4 = Serious Problems).

On-farm Head Survey and Analysis Tool (On-Farm Survey)

The purpose of the On-Farm Survey is to collect information needed to determine if the current flow at the farm turn-out is sufficient to allow for efficient on-farm irrigation. The tools utilized for this survey are On-Farm Survey Rating Form, and On-Farm Survey Spreadsheet.

As for the previous tools, the Manual reports a suggested procedure and additional comments. For example we recommend that answers should refer to a typical field in the scheduling unit, and during peak irrigation month. An example of results of the application of the On-Farm Survey is reported in Figure 5. Once again, forms are filled using codes.

An On-farm water delivery schedule calculation procedure is also available in the Manual. Additional data are needed to complete this calculation, which can be collected using recommended forms and procedures reported in the Manual

Table 2. Concrete Canal Evaluation data summary in the Iraq case study, for Main Canal (MC) and Branch Canal (BC). Column 10 is the rating for the general conditions (0 = Excellent, 1 = Good, 2 = Fair, 3 = Poor, 4 = Serious Problems)

QUESTION																							
GENERAL					CANAL RIDER				FIELD														
1_ID	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19a	19b	20	21	22a	22b
MC_0_4	0	4	0	1	1982	0	1	1A	2	2	1	0	2	1	0	0	2	1	2	3	1	1	10
MC_4_10.5	4	10.5	0	0	1982	0	1	1A	2	2	1	0	2	0	0	0	1	1	1	2	0	0	8
MC_10.5_13.5	10.5	13.5	0	0	1982	0	1	1A	2	2	1	0	2	1	0	0	1	1	1	3	1	1	8
MC_13.5_15	13.5	15	0	0	1982	0	1	1A	2	2	1	0	2	1	0	0	1	2	2	3	1	1	4
MC_15_16	15	16	0	0	1982	0	1	1A	2	2	1	0	2	1	1	0	1	1	2	3	1	1	3
MC_16_17.5	16	17.5	0	0	1982	0	1	1A	2	2	1	0	2	0	0	0	1	2	1	3	1	1	2
MC_17.5_19.6	17.5	19.6	0	0	1982	0	1	1A	2	1	1	0	2	0	0	0	1	2	2	3	1	1	4
BC_0_3	0	3	0	0	1982	0	1	1A	2	2	0	0	2	0	0	0	1	1	1	2	1	1	9
BC_3_5.4	3	5.4	0	0	1982	0	1	1A	3	2	1	0	2	0	0	0	1	1	2	2	1	1	15
BC_5.4_6.3	5.4	6.3	0	0	1982	0	1	1A	1	1	0	0	2	0	0	0	1	1	2	2	1	0	1
BC_6.3_6.9	6.3	6.9	0	0	1982	0	1	1A	1	1	0	0	2	0	0	0	1	1	1	2	0	0	0
BC_6.9_11.1	6.9	11.1	0	0	1982	0	1	1A	1	1	0	0	2	0	0	0	1	1	1	2	0	0	6
BC_11.1_12	11.1	12	0	0	1982	0	1	1A	1	1	0	0	2	0	0	0	1	1	1	2	0	0	0
BC_12_12.3	12	12.3	0	0	1982	0	1	1A	3	3	1	0	2	1	0	0	2	2	2	2	1	1	1

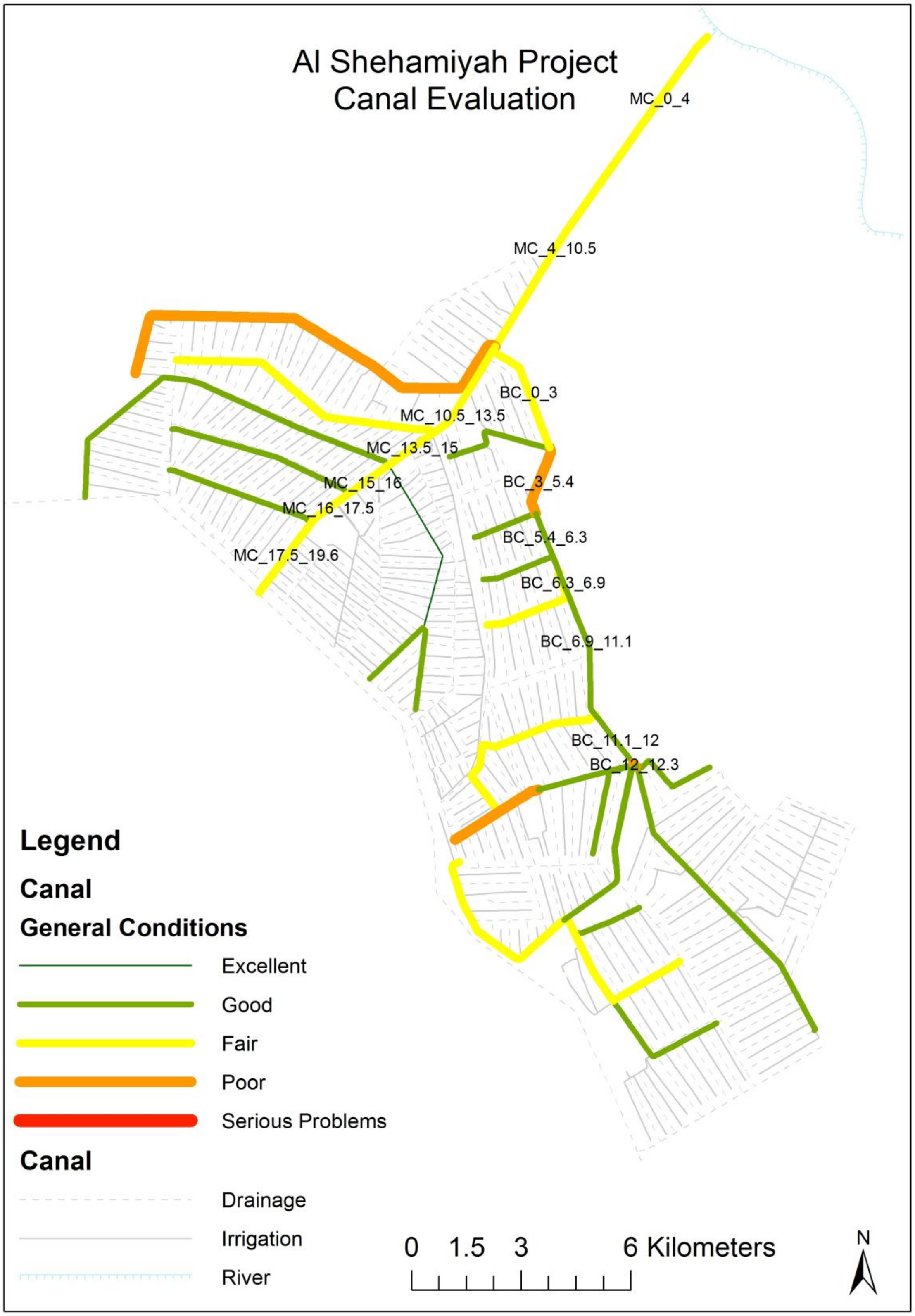

Figure 4. Example result for general conditions in the Canal evaluation (concrete canal) in the Iraq case study. Rating IDs are shown for the Main Canal and the Branch Canal

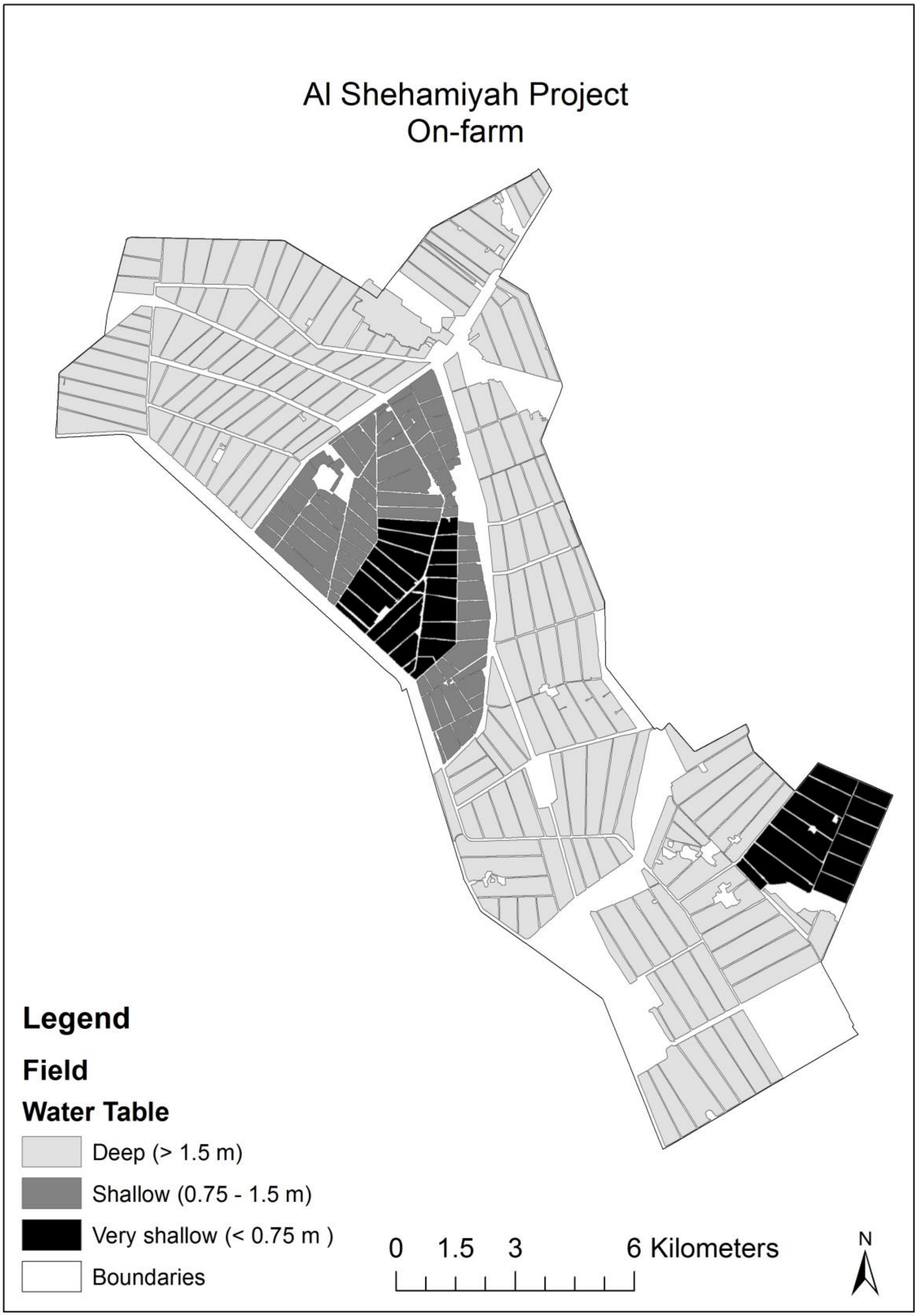

Figure 5. Example result for On farm survey in the Iraq case study: Water Table depth

GIS MAPPING

There is no GIS for irrigation schemes in Iraq. GIS is an essential component of the RIP, and we recommended a basic structure and a procedure to build it. Several comments are also included in the manual to guide the user, such as edit at a scale 1:5,000 or larger, use snap control when creating hydraulic network features, or draw canals features always in the direction of the flow.

PRIORITIZATION OF CANALS FOR LINING

In this study conducted in the Lower Colorado River Authority (LCRA) in Texas, we adopted the general procedure suggested in the RIP and conducted several surveys with LCRA personnel. We then updated and verified the methodology based upon field reconnaissance and GIS analysis. A 3-point ranking scale was used as an indication of the seriousness of expected seepage losses based on the following factors:

- Canal use frequency.
- Severity and cause of seepage.
- Visual indicators of seepage.
- Soil maps analysis.

Where:

- 1 = Highest priority, when at least two factors have maximum rating (ex. daily frequency, high seepage severity, serious visual problems).
- 2 = Priority level 2, when at least one of the factors have maximum rating, and canal is used at least yearly.
- 3 = Priority level 3, all other identified seepage locations where seepage is likely occurring.

Figure 6 gives the grouping of canals by priority for detailed seepage lost analysis: Nine (9) segments have priority level 1 (highest), for a total of 10 miles; Five (5) segments have priority level 2, for a total of 4.2 miles; and Ten (10) segments have priority level 3, for a total of 9 miles.

Five (5) segments, for a total of 4.1 miles, have been classified as likely having non-seepage losses, and mostly due to capacity and overflow problems. Some visual indicators of seepage losses are shown in Figures 7 and 8. Quantification of water savings from the lining of these canals requires further detailed analysis, such as soil detailed analysis (i.e. texture, infiltration, hydraulic conductivity) and flow measurements.

We found also non-seepage/leakage related problems. It is difficult to deliver water to about 7,000 acres of irrigated land due to land elevation problems, siltation at the farm turnout, and ruts made in canal embankments by cattle, and damage caused by cattle is widespread (Fig. 9 and 10).

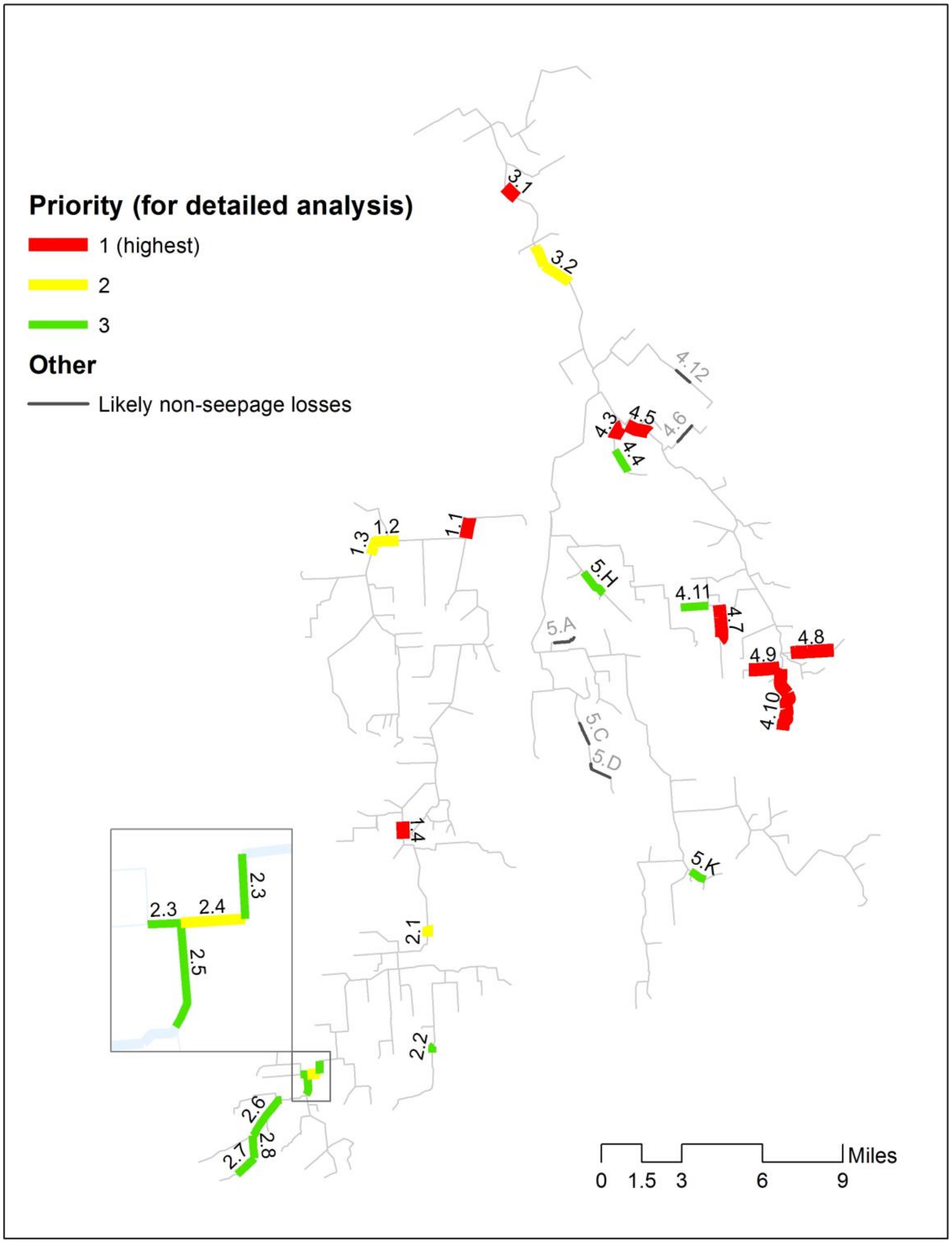

Figure 6. Rating of canal segments based on highest priority for detailed analysis in the Texas case study. Also shown are segments that likely have non-seepage water losses (such as due to overflow)

Figure 7. Seepage observed in canal embankment due to pocket gophers (4S7, top), and a crayfish burrow (4S5, bottom) in the Texas case study. Arrows identify the point of seepage

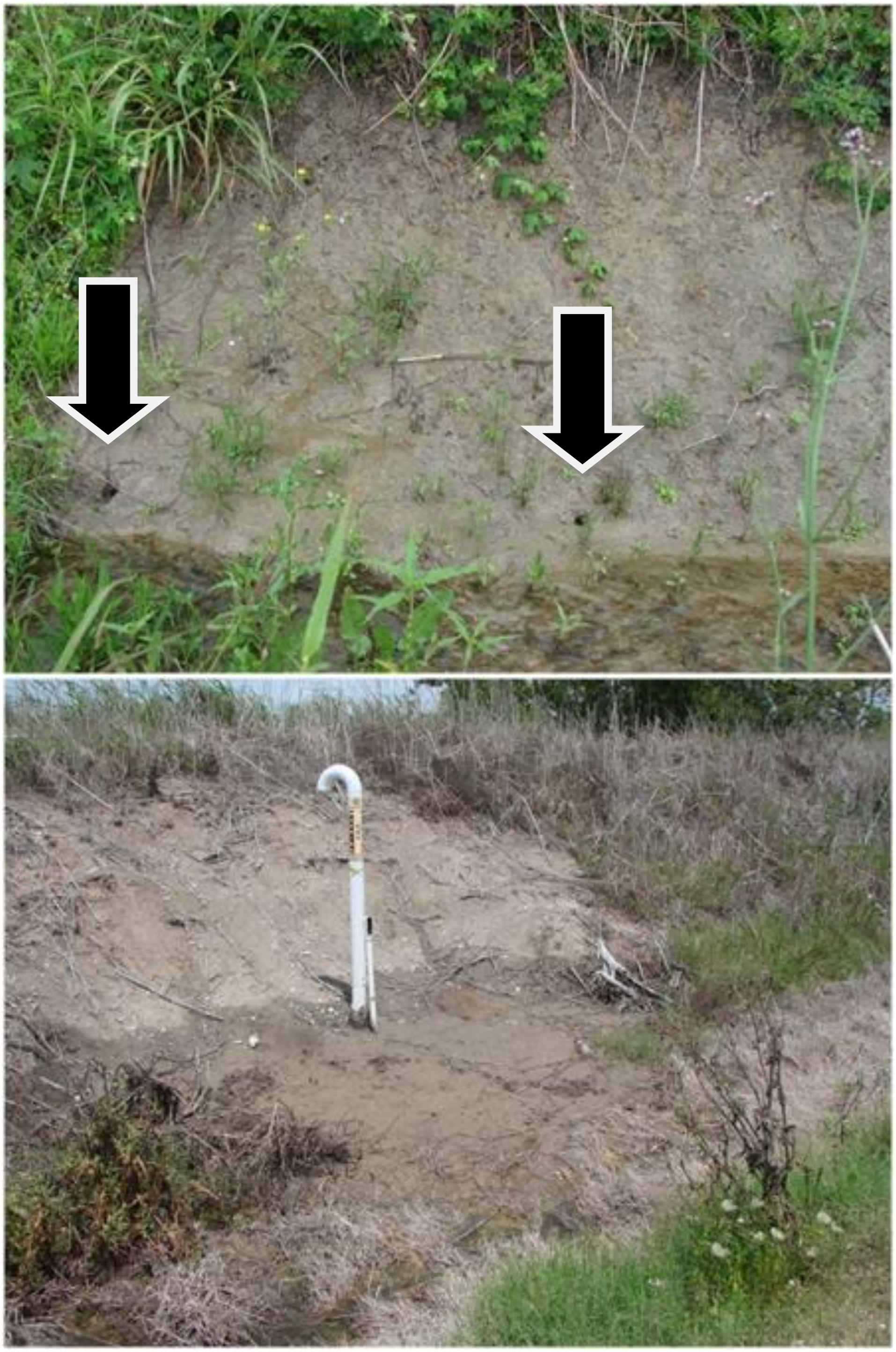

Figure 8. Seepage observed in canal embankment due to crayfish burrows (1S4, top), and pipe crossing (4S5, bottom) in the Texas case study. Arrows identify the point of seepage/leaks

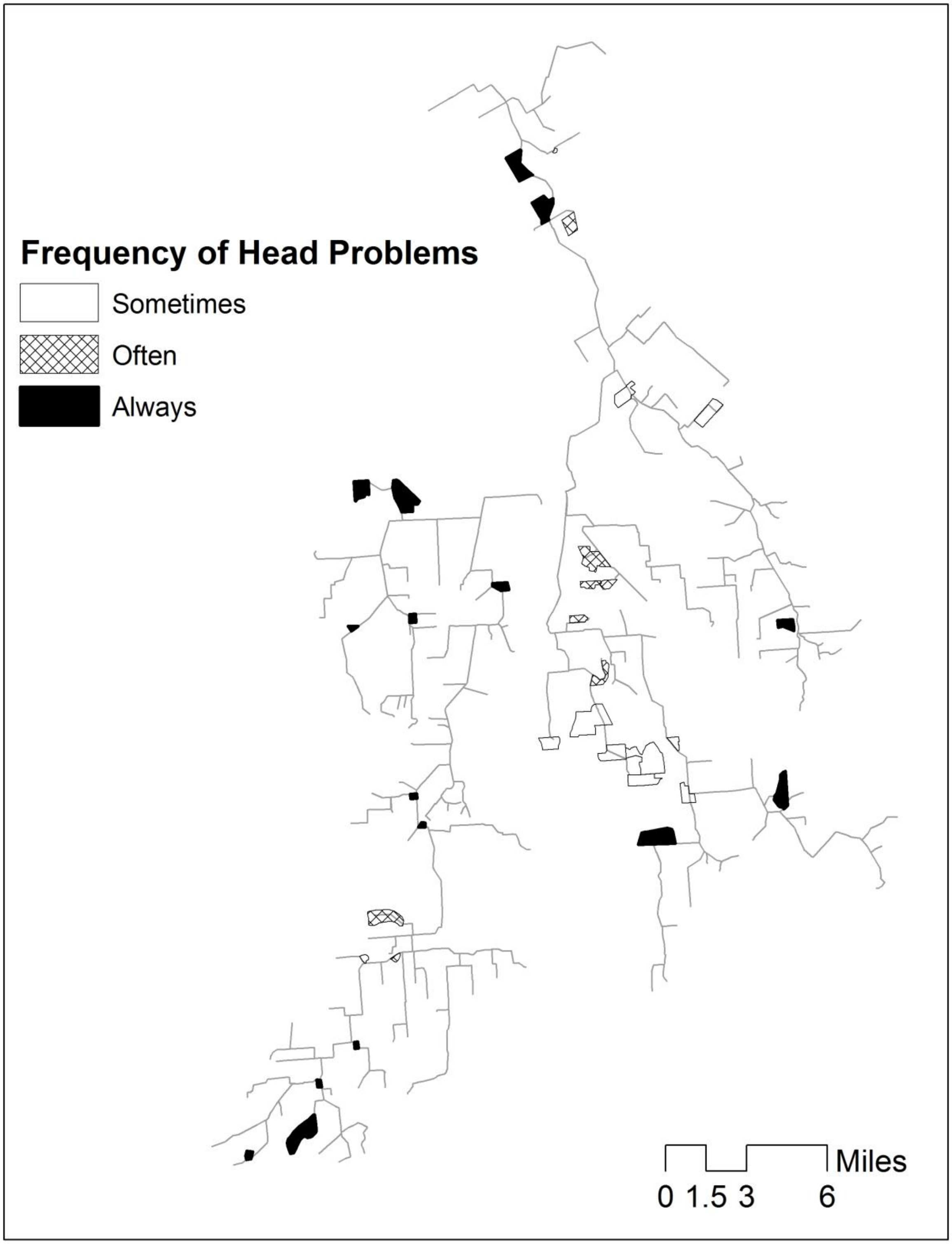

Figure 9. Frequency of Head problems in the Texas case study

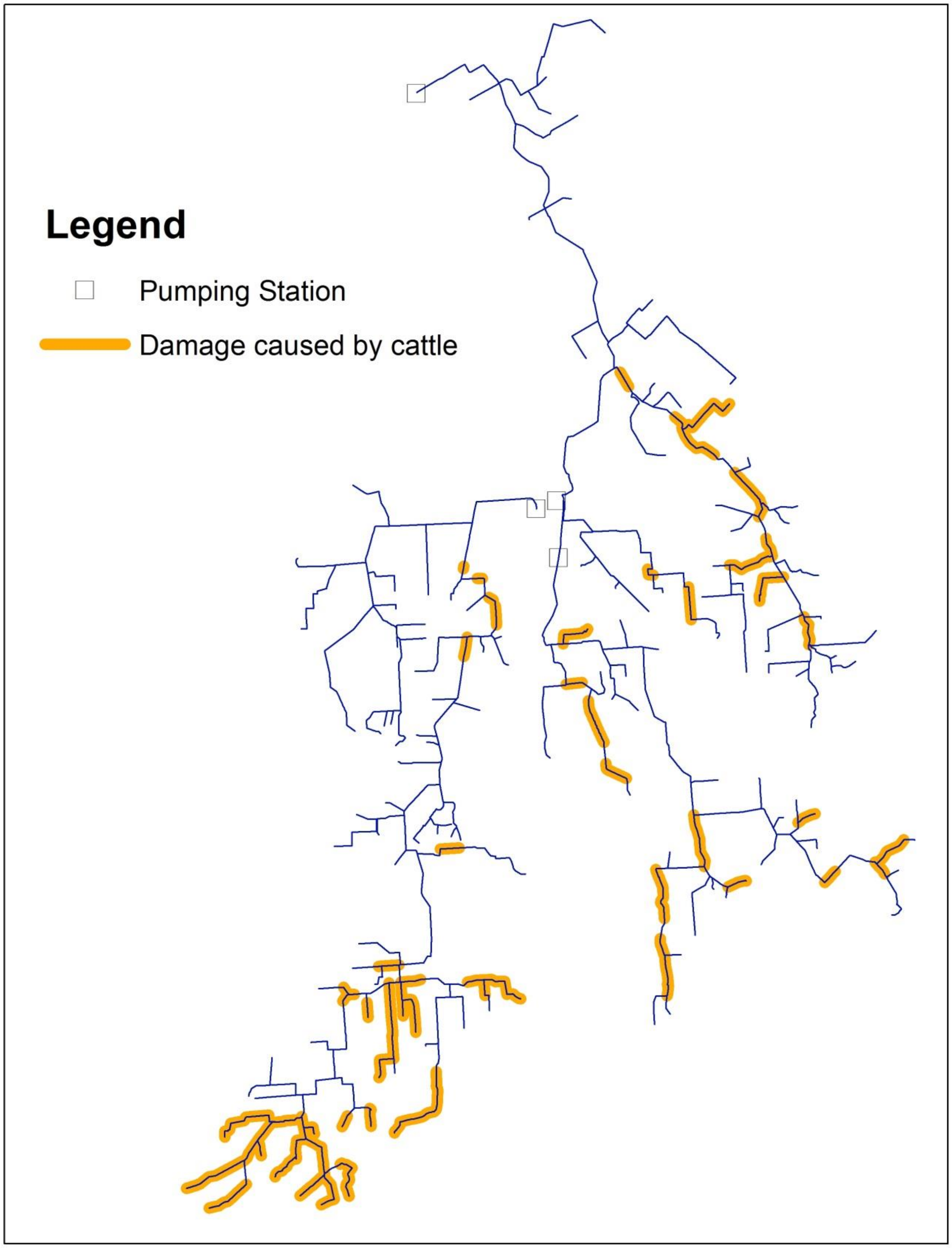

Figure 10. Canal segments damage by cattle in the Texas case study

CONCLUSIONS

The application of the RIP to the Iraq irrigation schemes allowed identifying priorities to be addressed to improve water delivery efficiency. It also provided an organized structure of data that can be further developed in more complex analysis.

All data in the RIP is interconnected and easily modifiable by a trained person, and results can be automatically updated with new data. This is the case of water delivery scheduling, which can be recalculated when detailed flow rate measurements or other field data becomes available.

By applying the RIP to the Gulf Coast Irrigation Division of the Lower Colorado River Authority (LCRA) in Texas, we identified 27.4 miles of canals that are likely to have significant seepage losses and/or leaks. These canals were ranked by priority for further analysis. We also identified non-seepage conditions and problems. Head problems resulting in insufficient flow were found that affects about 7,000 acres of irrigated land. Cattle damage is widespread in the South West and South East Sections of the Division.

Acknowledgements

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IWREDSS, A User-Friendly Water Allocation Software Package

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Abstract

User friendly water management software packages have proven to be helpful tools in managing water resources. They have been successfully used to perform complex analyses and to make informed predictions concerning consequences of proposed actions. In this paper, we describe a User-Friendly Computer Based Water Management Software Package, IWREDSS. This package was developed using two object oriented high level programming languages, Java and Visual Basics, and a spatial geo-spatial analysis software, ArcGIS.9.x version 1.0 and 10.x version.2.0. The model estimates irrigation requirements (IRR) perennial and annual crops based on site specific soil and weather information for different irrigation systems. IWREDSS has been successfully calibrated and validated using different data sets. A special version of IWREDSS has been used to calculate crop water allocation in Hawaii. A second version of the model developed for Texas will be presented. Results of the model compared favorably with those reported in the literature.

Introduction

Accurate measurement and estimation of water requirements for different uses (agricultural, domestic, or industrial) is a vital component of any water management program. Site specific investigations have been conducted to quantify water uses across all these areas; however, most of these results are commonly site specific, dependent on climatological and edaphic conditions, and costly in time and resources. Numerical water management models based on sound physical theories are practical management tools that have been proven to be useful in quantifying past, current and future water uses for different users. These numerical water management tools combine the subtlety of human judgment combined with the power of personal computers to allow more effective use of available data and account for more complexity.

In addition, these numerical models increase the accuracy of estimates to a level beyond human best judgment. Recent developments in Object oriented programming languages, i.e., Java, Visual Basics, and spatial analysis software, i.e., geographical information systems (GIS), and enhanced computational capabilities present the opportunity to apply hydrological and simulation models to enhance and optimize water supply and river basin managements, and to study impact of management intervention.

IWREDSS version 1.0 (Fares, 2007) and 2.0 (Fares, 2013) are two irrigation water management tools that have been used to calculate irrigation water use for different land uses in Hawaii. IWREDSS 1.0 and 2.0 are the GIS enhanced IManSys (Fares and Fares 2012). IManSys is based on the agricultural field scale irrigation requirements simulation (AFSIRS) model (Smajstrla and Zazueta, 1988). Irrigation requirements calculated using IManSys are more realistic because IManSys accounts for two important components of the water cycle, i.e., surface runoff, and rainfall canopy interception. It also includes others features for evapotranspiration potential calculation using different models (e.g., Panman Monteith Equation, ETM (Fares, 1996)) either daily complete weather data or daily minimum and maximum temperatures.

Rainfall canopy interception is the portion of gross rain that is intercepted by vegetation and evaporated without reaching the ground (Gash, 1979); it approximately represents 20% of net evaporation from the earth land surface (Choudhury et al., 1998), and 25-40% from temperate forests (Linacre and Geerts,1997). Consequently, It is one of the major components of water cycle. Rainfall canopy interception varies as a function of rainfall amount and intensity, and land cover; for instance, Leuning et al. (1994) reported a wheat rainfall canopy interception of 30%. However, Safeeq and Fares (2012), reported observed canopy interception varying between 23 and 45% for a Hawaiian forest with a native and a non-native plant species mixture. The canopy can retain only a certain amount of rainfall, the so-called The maximum storage capacity, Smax, is calculated as a function of the leaf area index (LAI) using the following equation of Dickinson (1984): Smax = 0.2 * LAI.

Runoff is a major component of the water cycle at the plot, field, or watershed scales. For instance, under semi-arid condition, the average annual runoff is about 10% of the annual rainfall; however, it can be as high as 70% of a given rainfall event. Runoff widely varies according to the seasonal distribution of rainfall, catchment characteristics (shape, size, steepness), and vegetation type and density (Edwards et al., 1983). IManSys calculates surface runoff using SCS curve number method (SCS, 1985 and 1993).

Site specific irrigation water requirements, determined by IManSys, are calculated based on plant growth parameters, soil properties, irrigation systems, and long-term daily weather data (rain, and potential evapotranspiration). In case daily potential evapotranspiration data are missing, IManSys can calculate them based on daily temperature data using different models, e.g. ETM (Fares et al. 1996). IManSys requires several databases of soil physical properties, and plant growth parameters, irrigation systems, and canopy interception. IManSys was implemented in JAVA object oriented language. IMamSys output includes detailed net and gross IWRs, and all water budget components at different time scales (daily, weekly, biweekly, monthly, and annually) based on non-exceedance drought probability which is calculated from a conditional probability model that uses the type I extreme value distribution for positive non-zero irrigation values. More details about IManSys can be found in Fares and Fares (2012).

Accurate estimation of IWRs should use site specific input data; thus, the spatial distribution of major input parameters (e.g., rainfall, potential evapotranspiration, soil water holding capacity) should be used. Thus, there is a need for an irrigation water management calculation model that accounts for spatial variation of major water cycle components and the soil physical properties (water holding capacity of each layer, and the depths of all soil layers). Thus, the objectives of this work are to i) give an overview of a site and crop specific, variable scale, GIS-based water allocation decision support system, and ii) evaluate the performance of this model in determining (gross irrigation requirements, GIRs) for different crops under high spatio-temporal variations.

Model

The water management model IWREDSS version 1.0 (Fares, 2007) and version 2.0 (Fares, 2013) are based on IManSys which was developed to account for the spatial variation of the input databases used by IManSys, e.g., soil physical properties, rainfall, and evapotranspiration.

A daily water balance model

Based on a daily mass balance approaches (equation 1), IManSys, uses long-term historical daily rainfall, evapotranspiration, irrigation systems specification, soil physical properties, and crop parameters to calculate daily, weekly, biweekly, monthly and yearly gross irrigation requirement (G_IRR), which is also called irrigation water allocation. In addition, IManSys calculates all the other water budget components at the same frequencies of those of irrigation requirements cited above.

IManSys calculates the crop irrigation water demand as follows:

$$G\_IRR = \frac{ET_{crop} + Dr + RO + CI - R - Ge}{(1 - LR).fs} \qquad (1)$$

where ET_{crop} is the crop evapotranspiration, R is gross rainfall, CI is canopy interception, Dr is excess drainage below the rootzone, RO is surface runoff, Ge is groundwater contribution, fs is efficiency of irrigation method (e.g., 85% and 50% for drip and flood, respectively) and LR is the leaching requirement to avoid salt built up in rootzone. All terms are in mm.

How to use the software

This is a step by step procedure on how to use IWREDSS. Users need to follow these steps to use the software:

Step 1: Starts of the Software

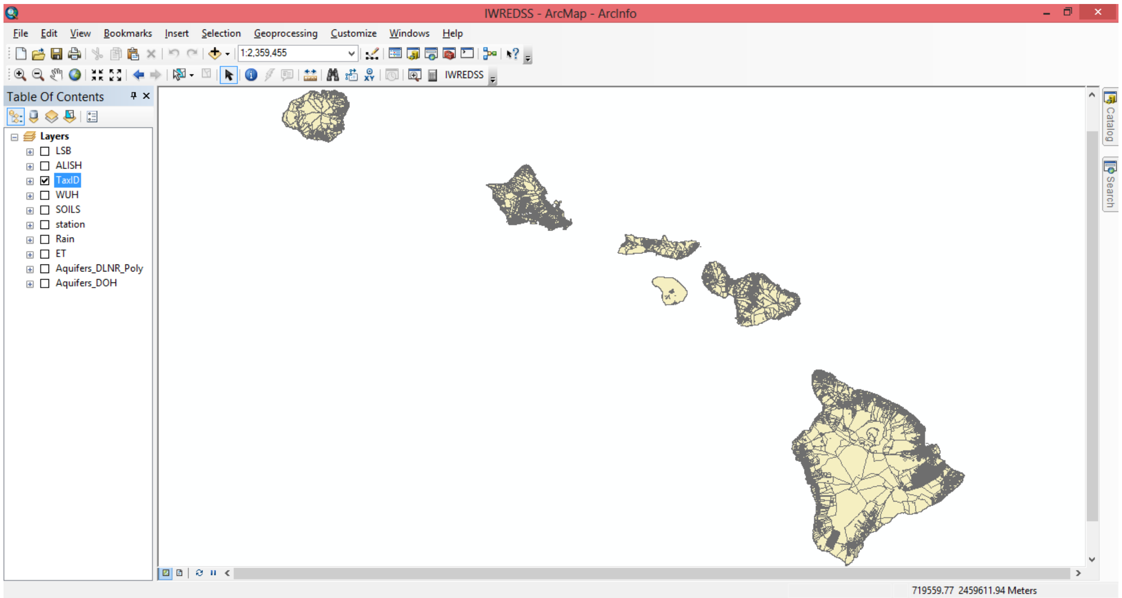


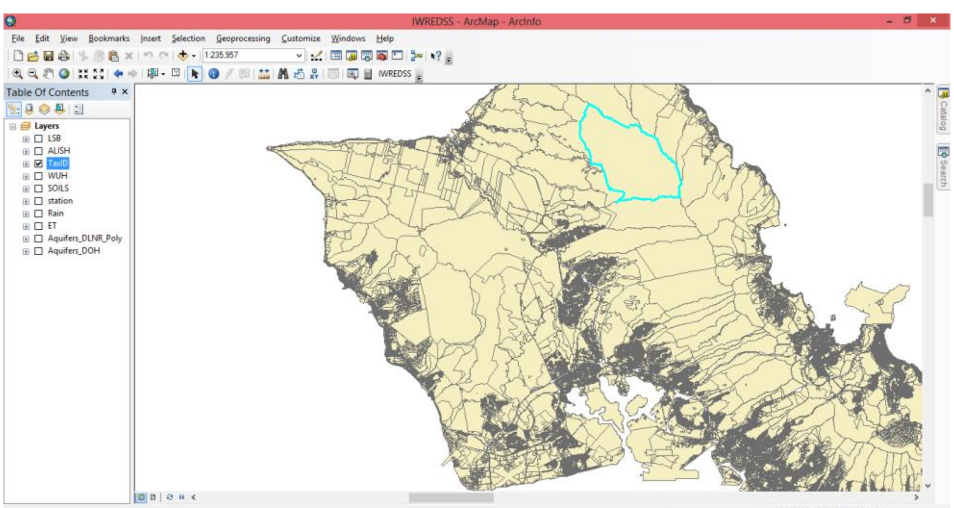
Figure 1. Through this Interface the user selects the location of interest for which irrigation water requirements will be calculated.

Step 2: Selecting the area of interest

Locate the area of interest from one of the Hawaiian Islands. It is suggested to zoom in the island of interest and click on TaxtID of the area of interest. There are two ways to select a TaxID area as follows:

Direct selection on the map.

First, Zoom in using the Zoom-in tool ; then, find the area of interest. irrigated/simulated. Second, use the feature-selection tool and select the area of interest as shown in Figure 2. Note that you can choose 1 area (TaxID) for simulation at a time.



Select by area from the attribute table. This method is detailed in Fares (2007).

Figure 2. Direct selection of the area for which irrigation requirements will be calculated.

Step 3: Set other input parameters

During this step, the user selects

additional input parameters most of which are done using a drop down menu. First, click on the tool button, this opens the window shown in Figure (3). Second, the user needs to input/select the following parameters:

Crop: User can select from the predefined list of crops given below:

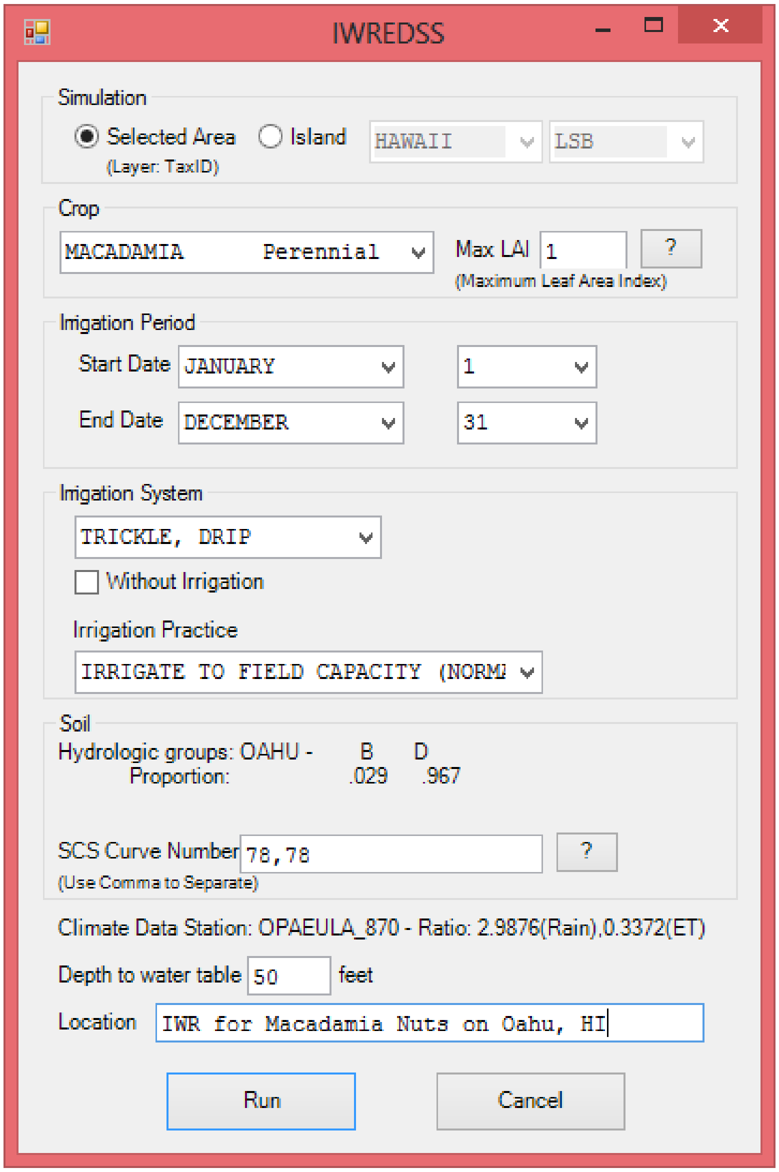


Figure 3. The main input parameters (crop type, irrigation period, LAI, irrigation system, and hydrological soil group) selection.

Perennial crops: The following crops are included in the database of IWREDSS: Generic Crop, Avocado, Bermuda Grass, Breadfruit, Citrus, Coconut,Palms, Coffee, Dendrob. in Pot, Dillis Grass, Domest.Garden, Draceane Pot, Eucalyp.,Old, Eucalyptus Young, Garden Herbs, Guava, Heliconia, Kikuyu Grass, Koa, Lychee, Macadamia, Mango, Papaya, St.Augustina, Ti, Turf, Golf, Turf, Landscape, and Zoysia Grass.

Annual crops

Generic Crop, Alfalfa Init, Alfalfa, Ratn, Banana Init, Banana Ratn, Cabbage, Cantaloup, Dry Onion, Egg Plant, Ginger, Lettuce, Melon, Peanuts, Peppers, Pineapp.Yearr-1, Pineapp.Yearr-2, Pumpkin, Seed Corn, Soybean, Sugar C.Ratn, Sugar C.Yr-1, Sugar C.Yr-2, Sunflowers, Sweet Potato, Taro (Dry), Taro (Wet), Tomato, and Water Melon.

For each crop type, different root zone depths and water use coefficient data are defined: for perennial crops, the parameters include irrigate crop zone depth, total zone depth, monthly crop water use coefficient (K_C), and monthly allowable water depletion (AWD). For annual crops, the parameters include initial crop zone depth, maximum crop zone depth, fraction of growth of 4 stages, crop water use coefficient (K_C) of 4 stages, and AWD of 4 stages.

Maximum leaf area index: The user should select the appropriate value of LAI, from the drop down list, this parameter is used to calculate canopy rainfall interception.

Irrigation period: User should specify the irrigation period that can be up to 1 year long; it can start at any month of the year and go around to the next year, i.e. starting date October of year one and ending date November of the following year.

Irrigation system: The users can select from a predefined list of irrigation systems given as follows: User-Specified System, Trickle Drip, Trickle Spray, Multiple Sprinklers, Container Nursery, Sprinkler Large Guns, Seepage/Sub-irrigation, Crown Flood, and Flood Irrigation for Taro.

Option for no irrigation: A provision is given to simulate the different water budget for rainfed agriculture. This option could be used for research purpose as to consider a natural hydrologic cycle where only rainfall is the input parameter and calculations are needed regarding effective rainfall, evapotranspiration, canopy interception, runoff, and drainage for range/conservation lands or other natural areas.

Irrigation practice: The users are given options to select irrigation practice. A dropdown menu provides options for irrigation practices including a) Irrigate to field capacity (normal practice); b) Apply a fixed depth per irrigation, and c) Deficit irrigation. In case option “b” is selected, the users are asked to enter the depth of irrigation in inches. Percentage of deficit irrigation is required to enter in case option “c” is selected.

Additional parameters: For the following list of the irrigation systems, additional parameters are needed. The system bed height is needed for crown flood irrigation; the depth to water table is needed for seepage irrigation system; and the flood storage depth must be included for the flood irrigation system.

The additional parameters (in inches) can be entered in a box next to the Irrigation System box. When extra parameters are not needed, this box is grayed out.

Soil hydrological groups and SCS curve numbers: All soil types in the selected TaxID area are grouped into four hydrologic groups (A, B, C, and D). The portion of each group of the soils in the selected area is given (for example, a selected area may have 11.3% of group B, 22.8% of group C, and 64.8% of group D). For each group, user has to specify the corresponding SCS curve number (CN). The curve number is used in the calculation of runoff. For details on determining CN values refer to IWREDSS User Guide (Fares, 2007).

By default, a CN value of 78 is given for each hydrologic group to remind users that they need to change these values to their correct values. A list of CN values for different cover and soil types is provided in Figure 4. User can refer to this list by clicking the “?” button next to the CN input box.

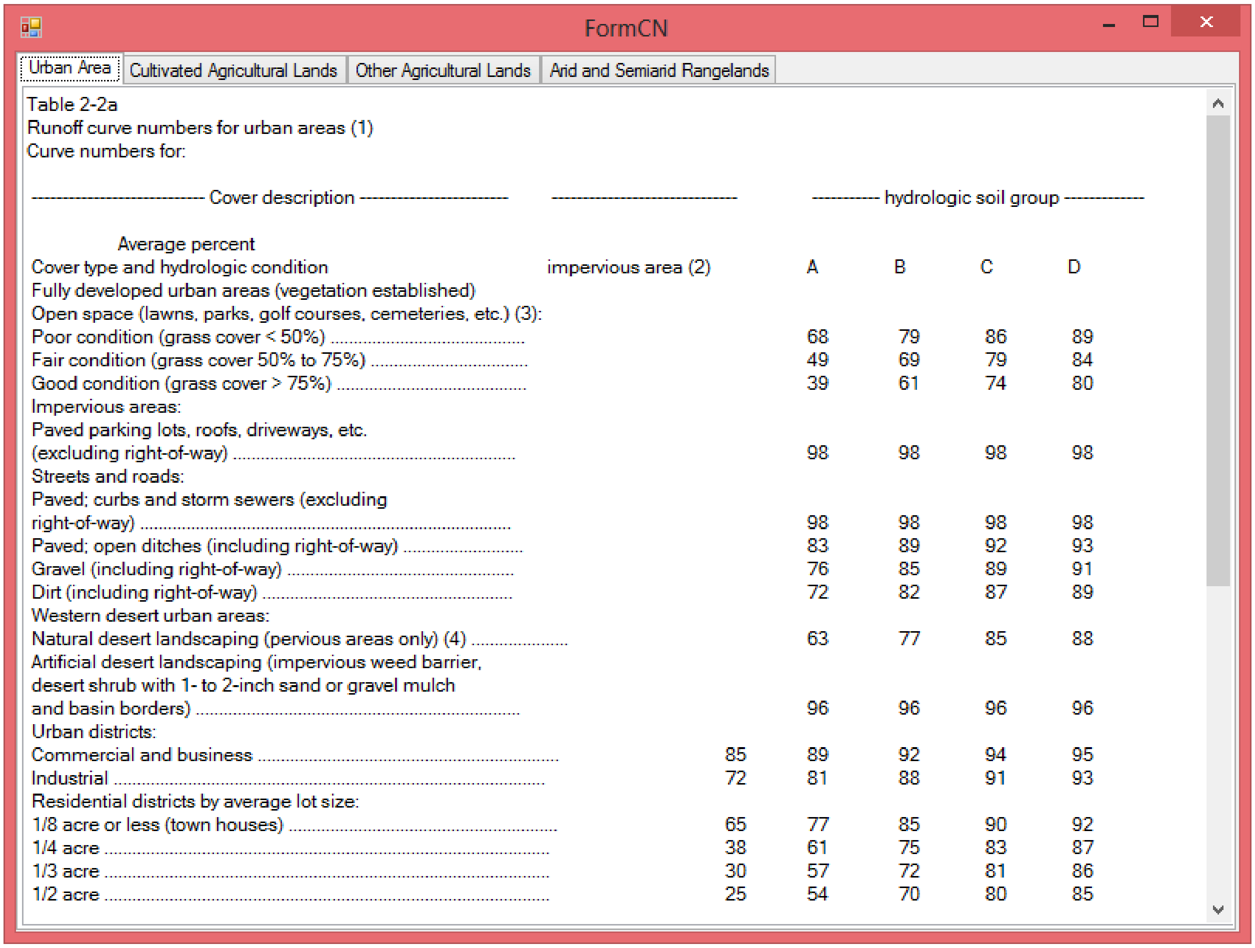


Table 2-2a
Runoff curve numbers for urban areas (1)
Curve numbers for:

------------------------- Cover description ----------------------	----------------------------	---------- hydrologic soil group ------------			
Cover type and hydrologic condition	Average percent impervious area (2)	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) (3):					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc.					
(excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding					
right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) (4)		63	77	85	88
Artificial desert landscaping (impervious weed barrier,					
desert shrub with 1- to 2-inch sand or gravel mulch					
and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85

Figure 4. Lists of CN values for different land cover under the four main soil types.

Depth to water table: This site-specific information is optional. It is recommended to use the default depth unless the precise value of water table depth is known. Note that the unit of water table depth is in feet.

Location: This is the name of location or area of interest; the user can type additional information to identify each simulation. The name appears in the beginning of the IWREDSS text output file.

Step 4: Execute IWREDSS

After completing the required inputs, the user can run IWREDSS by clicking the “Run” button to start simulation. A text box message will be prompted to the user about the state of simulation (fails or succeeds).

Step 5: Reading the result

After successful execution, a message (Figure 5) pops up giving user an option to view the results. A notepad text file opens after clicking the “Yes” button on the option message box. By default, the output file is saved in the subfolder “data” of the installation folder of IWREDSS with the default name as “IWREDSS_out.txt” and is automatically overwritten by successive execution. Therefore, the user is advised to save the results after every simulation with a different name by using File>Save as option in notepad.

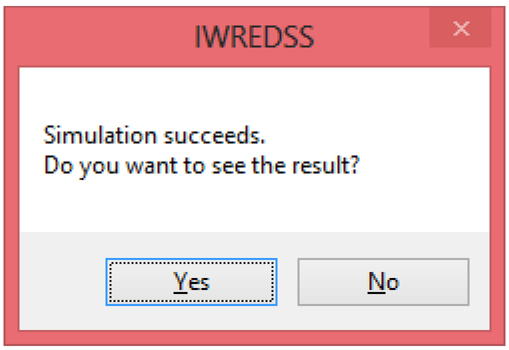


Figure 5. User’s Choice to Display Text Results.

The output text file contains three major sections: a legend table, simulation parameters, and simulation results. The legend table defines the abbreviations of parameters used in the output and their corresponding units. These parameters include the inputs parameters described in step 3 and the predefined parameters, e.g., crop type, irrigation system, soil type. The simulation results for yearly, monthly, bi-weekly, and weekly periods (Figure 6).

```
imansys_out - Notepad
File  Edit  Format  View  Help

         *******************************************************
         *                       SUMMARY                       *
         *******************************************************
         TMK  : 88001001
         SOILS: Ewa(0.078), Lualualei, extremely stony(0.198), Lualualei(0.029), Lualualei, stony(0.075), Lualualei, ston

                ANNUAL  IRRIGATION REQUIREMENT (INCHES)
          --------------------------------------------------------

                      WATER BUDGET COMPONENTS
          NIR    GIR     GAL_A  G_RAIN N_RAIN   ER   ER21   RO    INT   ETo    ET    DR
         29.2   29.2     791.6    33.3   26.7  19.9  19.1   5.4   1.3  48.9  49.0   6.9

                          GIR STATISTICS
 ACRES      UNIT              MEAN       MED.      XMAX      XMIN      50%       80%       90%       95%
         inch/acre           29.153    29.804    40.524    19.106    29.390    34.159    36.429    38.198
         Thou. gpd/acre       2.169     2.217     3.015     1.421     2.187     2.541     2.710     2.842
7104.00  Total thou. gpd 15407.553 15751.391 21417.200 10097.666 15532.916 18053.401 19252.839 20187.618

                          NIR STATISTICS
 ACRES      UNIT              MEAN       MED.      XMAX      XMIN      50%       80%       90%       95%
         inch/acre           29.153    29.804    40.524    19.106    29.390    34.159    36.429    38.198
         Thou. gpd/acre       2.169     2.217     3.015     1.421     2.187     2.541     2.710     2.842
7104.00  Total thou. gpd 15407.553 15751.391 21417.200 10097.666 15532.916 18053.401 19252.839 20187.618

 Note:- Irrigated area for the selected USER-SPECIFIED SYSTEM irrigation system is 1.0 of the total area


          MONTHLY  IRRIGATION REQUIREMENT (INCHES)
          --------------------------------------------------------

                      WATER BUDGET COMPONENTS
          MO    NIR   GIR     GAL_A  G_RAIN N_RAIN   ER   ER21   RO    INT   ETo    ET    DR
           1    1.0   1.0      26.3     4.1    3.3   1.9   2.2   0.6   0.1   3.0   3.0   1.4
```

Figure 6. Detailed Summary of IWREDSS Text Results.

At the end of the output file, there is a summary of the results. Actually, the simulation of IWREDSS is based on one soil type. Thus, if there is more than one soil type for a particular area (or TaxID), IWREDSS calculates irrigation requirements for each of these soils independently. The total irrigation requirement for the area of interest is a weighted average of all the soils available in that area using the following formula:

$$IRR = IRR_1 * A_1 / A_T + IRR_2 A_2 / A_T + \ldots + IRR_n * A_n / A_T$$

where IRR_i , A_i are the calculated irrigation requirements and the area occupied by i-th soil, respectively; A_T is the total area of the different soils available in the total area of the TaxID of interest. Note that IWREDSS does not simulate irrigation requirements for the non-arable parts of the area of the TaxID. The list of all the simulated soil types and corresponding proportion of each of them are given in the beginning of the summary section of the report.

IWREDSS uses calculated daily irrigation water requirements to calculate statistical parameters and probabilities of occurrence of IRRs for various time periods (i.e., weekly, bi-weekly, monthly and yearly). Summary of IWREDSS results provides IRRs for different probability levels, e.g. 50% (2 year return period), 80% (5 year return period), 90% (10 year return period) and 95% (20 year return period) probability of

GIRs. The 80% probability level (1 in 5 year return period) is recommended by USDA-NRCS and is also used by the irrigation industry when designing irrigation systems; thus, it was adopted for the recommended crop water allocation. The summary table also provides information on irrigation season, irrigation system, climate database, TMK, soil data, and other parameters used.

Step 6: Plotting the result

Switching from the text output file to ArcMap .The user is prompted to plot the results (Figure 7). The results are plotted on the map based on the yearly irrigation requirements for different soil type in the TaxID area.

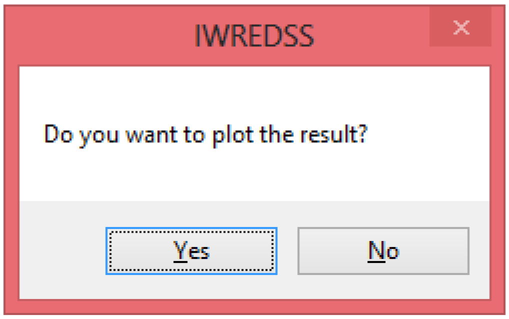


Figure 7. User's Choice for a Graphic Display of Results.

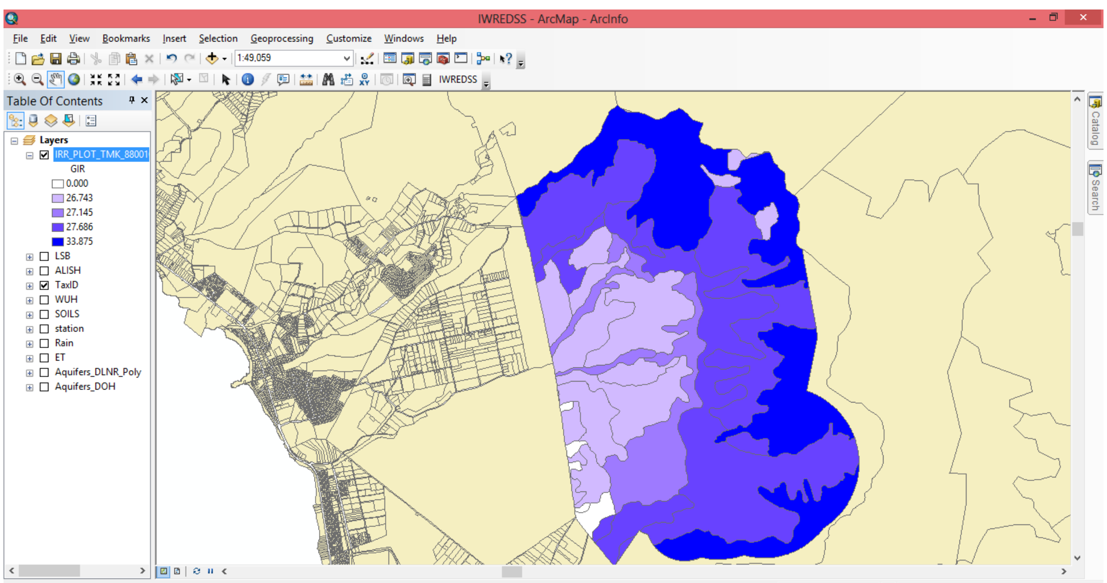


Figure 8. Graphic Display of IRRs Results and the Surrounding Properties.

An example of a color map plotting the results is given in Figure 8. The user can visualize the results on an enhanced option (Figure 9) by clicking the button to zoom to the whole TaxID Area.

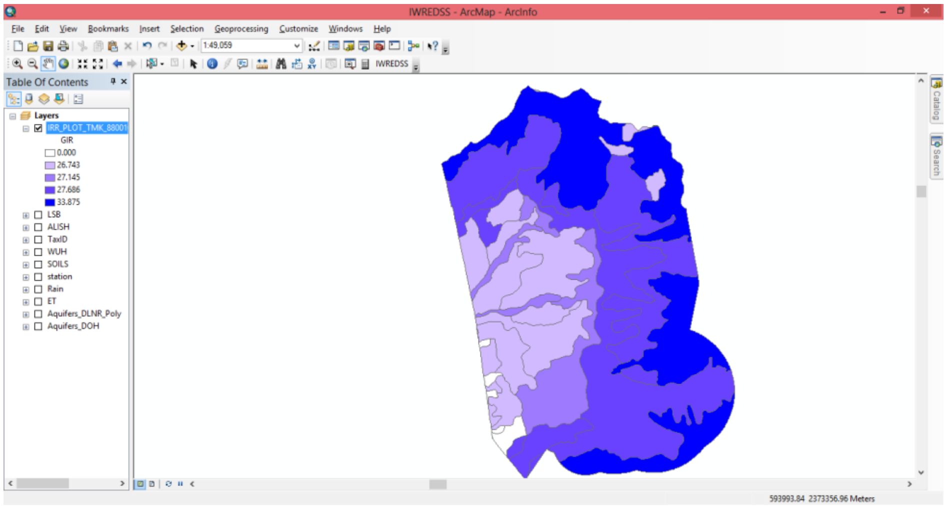


Figure 9. Irrigation Requirement Results of the Area of Interest Only.

IWRDESS was calibrated and validated with irrigation data estimates from Hawaii USDA-NRCS Handbook 38 (USDA-NRCS, 1996). These data include irrigation requirements maps for some crops on the major Hawaiian Islands. Irrigation requirements calculated with IWREDSS for different crops grown under specific to Hawaiian Islands are in close agreement with those estimated by USDA-NRCS Handbook 38. The relative small differences between the two datasets could be due to several factors including spatial and temporal variability of rainfall, evapotranspiration, and soil physical properties, and interpolation methods used to estimate rainfall and evapotranspiration.

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Using Collected Rainwater for Irrigation

By: Robert Drew, Founder Ecovie Environmental LLC

Abstract:

Rainwater collection is a proven water source for irrigation. Applying some basic principles, some of the pitfalls of rainwater collection can be avoided. Following water collection guidelines of ARCSA and some basic guidelines for pumping controls and city/well water back up, avoids many of these pitfalls. This paper is based on in the field experience integrating residential and commercial scale rainwater systems.

Experience troubleshooting poorly designed rainwater systems shows that the most likely culprit leading to unreliable performance is pre-filtration. If pre-filtration is non-existent or done in a way that passes debris, then issues arise with irrigation valves plugging over time and with pumping. Sometimes, filters blind over with debris which limits water capture. The answer to this is either more frequent cleaning or installation of self cleaning filters (usually preferred).

Pump selection can be an important consideration. If there is an existing irrigation system, flow while running should be checked along with an estimate of water flow. This gives a specification for pump selection in PSI and flow, which in turn can be matched with pump curves. For new installation, the expected flow and PSI should also me estimated to choose the correct rainwater pump.

Back up can take many formats. This paper presents three common methods. First, dual irrigation master valves are used, one for city water and the other for rainwater. A float switch in the rainwater tank tells which valve to open for an irrigation cycle. The second uses various forms of pressure reduction valves. The third employs a three way valve to switch between two water sources based on rainwater tank level.

Keywords: Rainwater Harvesting, Pump Controls, Water Filtration, Backflow Preventers

Rainwater collection is growing as a means of irrigating landscapes. While the concept is fairly straightforward, there are a number of considerations that are often overlooked, especially by those that are integrating rainwater collection systems to irrigation systems for the first time.

This paper doesn't dwell upon the basics of sound rainwater collection system design. The main focus of the paper will be the integration with existing and new irrigation systems, covering topics such as:

1. Water filtration requirements for rainwater systems feeding to irrigation.
2. Pipe and pump sizing to match city water flow along with pump control and reliability issues.
3. Reliable city water back up systems using the irrigation controls and other methods. The pros and cons of each type of method will be covered as well as the scenarios where one back up method might be preferred over another.

Pre-Filtration:

While we have come across a large number of issues with rainwater system design, by far the most common issue relates to filtration that is done before water goes to the storage tank. Pre-pritration arguably is the most important step to assure adequate water quality in a rainwater system. Good pre-filtration in turn leads to increased pump reliability and water capture efficiency. Poor pre-filtration can lead to clogged or poorly functioning irrigation valves.

To achieve good pre-filtration, follow ARCSA guidelines of around 350 microns screening. Self cleaning pre-filters seems to be preferred and definitely improve up time and reduce maintenance, although they cost more.

Pump Selection:

Pump selection seems like a very straightforward exercise but can prove a point of pain between the rainwater collection installer and irrigation designer. The most important way to avoid issues is good communication regarding this interface. Clearly defining specifications and expectations goes a long way to avoid issues. Having said that, it is important to have the best possible information to be able to match rainwater flow and pressure with that of back up water and with the requirements of the system. In many cases, the easy way out is to over specify pump size for rainwater and not worry. The can lead to excess capital cost and possibly over complication of the system, which leads to maintenance and reliability issues.

Also, if there is a large discrepancy between the rainwater and alternate water supply pressure, then the irrigation system should be designed to the lower flow.

Back Up Water:

Most serious rainwater systems have a back up water supply. Usually this will be a municipal water source. There are quite a large number of ways to provide back up water. Here, we will go in depth on three proven ways that actually work well. First, a dual master valve set up can be installed on the irrigation system. This is done by having one master valve on the rainwater and another on the city water. When it is time for an irrigation cycle to begin, a float switch in the rainwater tank tells which valve to open to provide water for irrigation. If there is water in the rainwater tank, rainwater is used. Otherwise, back up water is used. This may be the lowest cost solution depending upon location of the various valves and the rainwater tank.

The second method involves using a form of pressure reduction valve to initiate the use of back up water. If rainwater flow and pressure is not sufficient for any reason, the PRV allows back up water to flow. There are some valves specially designed for this purpose. The biggest benefit of this solution is that back up water is provided for any reason that rainwater is not available including low tanks level and pump not running. Installation is also fairly straightforward.

The third method is to use a 3 way valve which is positioned using a level switch or level indicator in the rainwater tank. When there is water, the valve positions for rainwater use. If not, it is positioned for back up water use. This method is commonly used in commercial applications and fairly widely for residences as well.

Another method we have seen used is to put a small amount of back up water in the rainwater tank when it empties. This is typically done using a solenoid valve receiving a signal from a float switch or tank level indicator or from a simple float valve set up. In either case, there can be serious issues with reliability and with high water use in the event of valve or control failure. Float valves in particular can fail open to cause a very high water use until the problem is found. Another consideration is to always design a manual back up for the purposes of trouble shooting and to provide back up water in the event of a power outage or other type of system failure.

Rainwater Harvest Makes Sense and Cents (and Dollars)

David Crawford, President

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Abstract. *Rooftop rainwater harvesting has moved beyond the leaf-filled rain barrel sitting at the corner of your home's porch to a cost-effective, scalable system. As water scarcity issues and the need for protection of the declining quality of surface and groundwater are becoming more pressing, we are now realizing that rainwater harvesting addresses another important concern, stormwater. Captured rooftop rainwater turns unwanted stormwater runoff, which would otherwise require handling in stormwater treatment facilities or contribute to stream erosion and lake sedimentation, into a valuable resource, useable for both indoor and outdoor purposes. In addition, rainwater harvesting reduces the total volume of potable water demand, thereby cutting water treatment costs and energy use. By using non-potable water for non-potable uses, it provides a viable alternative to traditional centralized water treatment and distribution, which are inefficient in both water and energy.*

In addition to the economic value of reduced water supply costs, making rainwater harvesting part of the entire stormwater management design can result in significant savings on stormwater fees and reduce the cost of other site stormwater practices. The long-term economic feasibility of such projects depends on minimal system servicing and high-quality components to divert, collect, and store water. A consistent design standard, including pre-tank filtration and proper water storage, uptake, and overflow, will preclude many of the common pitfalls in design, leading to more cost-effective, sustainable systems. Systems which provide a reliable, high-quality water source will encourage rainwater harvesting as a lasting environmental solution to save water, energy, and *money.*

Keywords. Rainwater harvesting, stormwater management, tanks, water conservation, groundwater, erosion, sedimentation, runoff, irrigation, LEED certification, water quality, site management, filtration, water storage, sustainability, building machine

Environmental Benefits

Rooftop rainwater harvesting has moved beyond the leaf-filled rain barrel sitting at the corner of your home's porch to a cost-effective system, scalable to any size. As water scarcity issues have increased, the need for water conservation and protection of the declining quality of surface and groundwater initially created interest in rainwater harvesting. These issues are becoming even more pressing, and we are now realizing that rainwater harvesting addresses another important concern, stormwater management. Captured rooftop rainwater turns unwanted stormwater runoff, which would otherwise require handling in stormwater treatment facilities or contribute to stream erosion and lake sedimentation, into a valuable resource, useable for both indoor and outdoor purposes, from flushing toilets to irrigation. In addition, rainwater harvesting reduces the total volume of potable water demand, thereby cutting water treatment costs and energy use. By using non-potable water for non-potable uses, it provides a viable alternative to traditional centralized water treatment and distribution, which are inefficient in terms of both water and energy.

Economic Benefits

In addition to the economic value of reduced water supply costs, making rainwater harvesting part of the entire stormwater management design can result in significant savings on stormwater fees and reduce the size and cost of other site stormwater practices. Rainwater harvesting is also one component that can contribute to LEED (Leadership in Energy and Environmental Design) certification, and a number of LEED credits are available through rainwater harvesting systems. The economic and environmental benefits of rainwater harvesting, reducing the demand on an aging water supply infrastructure, saving energy, decreasing runoff, and preserving water quality, make it an integral part of whole-site water management.

Often, the primary cost savings associated with rainwater harvesting systems is based on the reduction in use of potable water from a municipality. Manassas Park Elementary School, located in northern Virginia, is an excellent example of potential cost savings due to potable water use reduction. Based upon comparison with a similar school located on the same campus, the facilities management team of the City of Manassas Park Public Schools believes that they are recognizing a savings of 1.3 million gallons of municipal water per year by flushing school toilets with harvested rainwater. Using water cost data from a similar municipality in Virginia, this scenario creates a situation where a cost savings of approximately 8,500 dollars per year can be realized (Authority, 2013). Further, because the domestic water that serves as a backup to the harvested rainwater used to flush the toilets is introduced at a "Day Tank", the municipal water service feeding the facility could be reduced in size. This potential reduction in tap and pipe size can have significant financial implications. For example, the reduction of a water line tap from a 3” to a 2” can result in over 30,000 dollars initial savings with additional monthly savings being realized as well (Lawson, 2012). Finally, it should be noted that across America, water rates continue to increase on a yearly basis. A 4% increase per year appears typical. While decreasing the amount of potable water that has to be purchased by a facility for non-potable uses is one way to save money through the use of rainwater harvesting, it is not the only way.

Rainwater harvesting can be an integral part of an overall treatment train for stormwater. Instead of simply detaining stormwater onsite for a period of time, rainwater harvesting allows water to be retained and reused on site. The Southwest Regional Jail in Roanoke County, Virginia illustrates this type of scenario. Initial cost estimates for a “traditional” stormwater detention system, comprised primarily of detention ponds, was approximately 240,000 dollars. The rainwater harvesting system and the rest of the integrated stormwater system that was installed cost 258,000 dollars. A cost savings of 11,675 dollars was realized in the first year of operation based on the cost of municipal water that did not have to be purchased. This system illustrates a payback scenario requiring less than two years (Sojka, 2009). After this point, the potable water that does not have to be purchased can actually be viewed as income. Using harvested rainwater for non-potable uses can allow for additional cost savings by viewing the rainwater system as an integral component of the building machine.

Harvested rainwater also has advantages over municipally processed water. Rainwater is inherently soft. As a result, the laundry operators at the Southwest Regional Jail report an approximate 70% reduction in the use of detergent and softener when operating with harvested rainwater. Since harvested rainwater is often stored in belowground tanks, it maintains a consistent temperature. At the jail, this fact was capitalized upon by utilizing this water which is consistently 58 degrees to cool the motors that operate the vacuum flush sewage system. Once the harvested rainwater passes through the heat exchanger to cool the motors, the now preheated water is utilized in the initial gross wash in the laundry and requires less heating to bring it to temperature, reducing the amount of natural gas required in the water heating process. When harvested rainwater is viewed as an integral part of the building machine, its advantages can be seen not only in potable water conservation and reduction of stormwater runoff but also in lessening the demands on other building systems. All of these attributes result in financial advantages for the building and its operator.

System Design

Rainwater harvesting is a suitable water source and stormwater solution for residential, commercial, industrial, and agricultural applications, and systems can be retro-fitted to existing buildings or integrated into new building designs. A simple, consistent system design, which preserves the quality of the rainwater, will allow it to be scaled to a project of any size, from a residential home to a commercial factory. The long-term economic feasibility of rainwater harvesting projects depends on minimal system servicing and high-quality components to divert, collect, and store water. A consistent design standard, including pre-tank filtration and proper water storage, uptake, and overflow, will preclude many of the common pitfalls in design, leading to more cost-effective, sustainable systems. A vertical pre-tank filter protects the quality of rainwater stored in the tank by preventing the introduction of debris. Build-up of organic debris in the tank leads to higher decomposition, low oxygen levels, and an increase in nutrient concentrations. This in turn can result in the development of odors as well as the growth of harmful bacteria in the tank (Lawson, LaBranche-Tucker, Otto-Wack, & et al., 2009). In a healthy rainwater system, the tank will never need to be emptied or cleaned as the water stored is of the highest quality and, thus, minimal maintenance is required for downstream filtration, maximizing the use of this natural resource.

Conclusion

As water rates continue to increase, the cumulative savings attributable to rainwater harvesting will increase as well. Thinking beyond the rain barrel to scalable rainwater harvesting system design that is part of the whole-site water management plan will help address ongoing issues of water quality, conservation, and sustainability. Modern rainwater harvesting is based on scientifically sound principles, and further understanding of the components necessary for a safe and sustainable water supply will ensure production of high-quality harvested rainwater. Systems which provide a reliable, high-quality water source will encourage rainwater harvesting as a lasting environmental solution to save water, energy, *and* money.

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Before It All Goes Down the Drain:

Case Studies of Rain Harvesting Use & Dry Weather Runoff Reuse in Santa Monica, CA

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Abstract. In a time of severe water shortages in many parts of the country, the City of Santa Monica has emerged as a leader in watershed management with numerous public and private projects that demonstrate the benefits of harvesting rain and dry weather runoff. This paper will examine local residential, multi-family, governmental and institutional sites that are using rain-harvesting techniques such as cisterns, rain barrels, and infiltration pits. Then we will examine how harvested water is distributed through the landscape with drip irrigation systems. Next we will look at how dry weather runoff is collected from streets, treated and used in overhead irrigation. We will reflect upon past successes and failures, look toward to the future of water, and explore how we can harness this precious resource now… before it all goes down the drain… carrying with it not only contaminants that pollute the ocean, but the opportunity to use a local valuable resource.

Keywords. Rain Harvest, Cistern, Rain Barrel, Dry Weather Runoff, Infiltration, Stormwater

Since 1991 the City of Santa Monica, CA has been creating and enforcing requirements for the design, construction, and long-term management of new and redevelopments in order to reduce urban runoff water and the pollution it contains. Urban runoff includes wet and dry weather flows on one's property or public right-of-way. The runoff occurs when water, originating from rainfall, washing activities or over-irrigation, runs into the surrounding aquatic environment. Pollutants such as heavy metals, nutrients, bacteria, organic compounds and trash, in automotive fluids, restaurant equipment, pesticides, lawn care products, debris, construction materials, pet wastes, and paint-related products are washed into our storm drain system and into the Santa Monica Bay on a daily basis, rain or shine. Urban runoff flows untreated from buildings, yards, sidewalks, roads, and parking areas into the greater watershed of our region – and all pipes, gutters and storm drains of our city end up in the Santa Monica Bay. Urban runoff is now the single greatest source of pollution to the beaches and near shore waters of the Bay.

One important way to address this problem is by managing the design, construction and long-term operations and maintenance of developments in such a way as to minimize urban runoff from the site. We do this by treating rainwater, stormwater and dry weather runoff as resources rather than a waste product needing to be quickly ushered offsite.

The design, construction and the long-term operations and maintenance of a development come together with the submittal and implementation of the Urban Runoff Mitigation Plan or Drainage Plan, an integral component of any permitted building project. A plan is required for any project that meets the definition of "new/re-development" as outlined in our City's Urban Runoff Pollution Control Ordinance. The Drainage Plan you submit acts as your road map to ensure that the projected urban runoff from your proposed project (property/parcel) is reduced through installation of permanent structural (e.g. post-construction) Best Management Practices (BMPs). BMPs promote the natural movement of water within an ecosystem or watershed, keeping precipitation onsite as much as possible, providing for permeability such that soil can absorb water falling onto the site, or it can be stored in cisterns for direct non-potable applications. The ordinance requires that new/re-developed parcels reduce the projected rainfall on all impermeable surfaces of the parcel up to a 0.75" storm event. Each development project is considered a micro-watershed within the greater watershed or drainage basin of the City. BMPs promote the concept of retaining as much rainfall on each site in order to minimize runoff.

Permanent BMPs harvest precipitation for non-potable uses – passive, indirect infiltration and direct indoor and outdoor authorized uses, such as irrigation and flushing. Residential units in Santa Monica are incorporating Low Impact Development (LID) strategies with BMPs to harvest rain either for treatment via infiltration (soil ecology does a wonderful job in neutralizing low-level or background concentrations of pollutants) or for use in landscape irrigation and indoor flushing after appropriate treatment. An inexpensive approach is to harvest precipitation in a rigid or collapsible container, like a rain barrel or series of interconnected barrels. Each barrel generally holds 50-75 gallons. A step up from a rain barrel is a small cistern that holds 200 gallons. Larger storage systems called cisterns come in different sizes and shapes. Cistern capacity is generally over 500 gallons. Some cisterns have thousands of gallons of storage space.

One example is a residential family home with two cistern tanks in the front and rear of the house connected to a sub-surface drip irrigation system. Each cistern is capable of holding up to 500 gallons of rainwater. Harvested water can be used for sub-surface irrigation. Homes with rain gutters directed to landscaped areas, or homes with no gutters at all, are required to mitigate volume onsite. The landscape is the solution and must have the proper storage volume above or below the surface to mitigate the required runoff volume.

Another example is a multi-family building cistern project built in 2008. It demonstrates the city's highest sustainable end use urban runoff strategy: direct use. By directly using runoff, one can reduce the demand for more valuable potable water, most of which is imported into Southern California from distant watersheds. Runoff from the roof is collected and piped through three downspout BMPs before entering the 5,000 gallon plastic box cistern wrapped with an impermeable layer, which is located beneath the landscape. A typical sub-surface infiltration pit for residential and commercial properties is a plastic crate or concrete vault structure to store precipitation. In this example, the sub-surface chamber was modified to retain the water rather than infiltrate it. The landscape includes climate-appropriate and native plants. Stored water is pumped to the landscape's sub-surface drip irrigation system. The multiple family units have saved 800,000 gallons of potable water since the installation. However, the project has not been without its share of problems. Tree roots have been discovered in the vault housing the pump, and the electrical conduit corroded causing the pump to fail. Routine inspection and maintenance of the system, or any system, is required to make sure it operates properly.

Rebuilt from the ground up, the Santa Monica Main Library opened in 2006. Runoff from roofs, decks and surface parking areas is collected and piped through 17 downspout filter BMPs before entering the 200,000 gallon concrete cistern BMP, which is located beneath the underground parking structure. Downspout filters are capable of removing some pollutants. Stored water is pumped to the library's sub-surface irrigation system. The landscape includes climate-appropriate and native plants. The surface parking lot has two BMPs to collect and filter water before it reaches the cistern: slotted drains and a StormFilter® catch basin. The catch basin contains a media-filled cartridge to filter soluble pollutants, as well as remove trash. All site runoff is directed to these four BMPs.

Airport Park is an example of a project that incorporates LID strategies with BMPs to harvest most stormwater for treatment via infiltration. This project is also an example of creating new park land in highly urbanized and built-out areas where impermeable hardscape previously existed, providing additional open spaces for recreational and water quality improvement activities. Opened on April 29, 2007, Airport Park has many BMPs throughout the park. The BMPs include Bay Boxes (i.e., Santa Monica's term for a filtering or infiltration device that protects water quality of the Santa Monica Bay) along much of the park perimeter as well as in other locations near impermeable surfaces, such as an adjacent tie-down airplane parking lot. The north and south parking lots use porous asphalt as the BMP, allowing runoff to infiltrate. The parking lots allow runoff to pass through the permeable hard surface and into the subgrade for infiltration, where soil ecology filters runoff and improves stormwater quality. The park also includes a synthetic turf soccer field, which eliminates the need for irrigation and saves water at a time of increasing drought concern, and drier and warmer weather predictions. The soccer field and the adjacent dog park can also absorb, infiltrate and treat urban runoff.

Another example is a city beach parking lot that was converted to a permeable turf surface for recreational activities to harvest and infiltrate parking lot runoff and also allow beach parking- a dual function parking lot. In the City's first Green Street, parking lanes are paved with pervious concrete. Pervious concrete, like porous asphalt or pavers on sand, allows parking and road runoff to infiltrate. Other ways to reduce parking lot pollution include curbless green strips and permeable pavement to capture and percolate runoff where possible. At Virginia Avenue Park, parking stalls with pavers allow parking lot runoff to infiltrate into the ground. Bio-filters for treatment and percolation are used throughout various sites in the City, too.

The City employs other strategies to mitigate urban runoff. Numerous alleys have pervious concrete in the center to allow runoff to infiltrate into the ground layer. Trench drains are routinely installed to collect and direct runoff from a roof, driveway or parking lot to an infiltration pit. Downspouts are modified to redirect roof runoff to landscaped areas (rain gardens) instead of directly connected to impermeable surfaces and the public right-of-way. Any construction project adding downspouts, gutters and sub-surface pipes directing stormwater to the curb face should have a French drain system of perforated pipe and gravel (some exceptions for public safety).

In Santa Monica, the storm drain system is separate from the sanitary sewage system. Storm drains are intended to take stormwater straight to the ocean to avoid area flooding and without treatment. Santa Monica is unique in that a high percentage (94%) of the dry-weather runoff is treated. The Santa Monica Urban Runoff Recycling Facility (SMURRF) cleans dry weather urban runoff from the City's largest flows, the Pico-Kenter and Pier Storm Drains, which drain 4,200 and 900 acres respectfully. The Pico-Kenter drainage also includes parts of the City of Los Angeles and the Santa Monica Mountains.

Dry weather runoff is created from excess irrigation, spills, construction sites, pool draining, car washing, washing down paved areas and residual wet weather runoff. The SMURRF treats and reuses most of the runoff during dry weather, up to 500,000 gallons of dry weather runoff daily. The recycled water is used for irrigation and dual plumbed office buildings. The primary objective of the SMURRF is to eliminate pollution entering Santa Monica Bay caused by dry weather urban runoff (storm drain low flows). Secondary project goals include: providing cost-effective treatment; producing high quality water for reuse in landscape irrigation and indoor flushing; raising public awareness of Santa Monica Bay pollution and the role of each individual in the watershed through appropriate educational exhibits; and constructing an aesthetically pleasing and functional facility with an appropriate emphasis on art and educational elements that attracts people while providing new access to the beach.

The treatment train is first "coarse" screened in a Continuous Deflective Separation (CDS) unit. Coarse screening removes large floating debris and trash (such a bottles, twigs, etc.) that typically flow down gutters into streets. "Coarse" screened flows are then pumped about a mile to the recycling facility. The first process unit is the Rotating Drum Screen. The Rotating Drum Screen removes fine floating particles (that escaped the coarse screening) greater than 0.04 inches in size. From the screen the water flows to the cyclone-type Grit Chamber. This unit removes grit and sand. Screening and de-gritting systems remove inorganic settleable material that may damage the downstream treatment processes and reduce the treatment efficiency. From the Grit unit the preliminary treated water is stored in the raw water storage tank. The raw water storage tank dampens the fluctuations in the influent flows, thereby allowing downstream filtration and disinfection processes to operate at a steady rate, and more efficiently. From the raw water storage tank the water is pumped to the Dissolved Air Flotation (DAF) unit. In this unit, compressed air is injected into the water at the unit inlet. As the water reaches the open tank surface, it reaches atmospheric pressure whereby fine air bubbles are released in the water. The air bubbles rise to the top and carry with it the oil and grease with the help of a flocculating agent. The oil and grease blanket formed at the DAF unit open surface is then skimmed off the top. From the DAF unit the water flows to the Microfiltration treatment unit. Here, the vacuum applied on perforated membranes forces the water through the membrane thereby "filtering" out the turbidity. The membranes have to be regularly back-flushed to clean pollutant "buildup." From the Microfiltration unit the water flows to the Disinfection process, which uses Ultraviolet (UV) radiation to disinfect the water. As the water passes by the UV lamps in series, UV light kills or neutralizes bacteria and viruses. The UV bulbs have to be periodically cleaned of the scale "buildup," or they will lose efficiency. Finally, treated water is stored in the "clean water tank," from where it is pumped into the distribution system for reuse. The daily reuse of runoff is about four percent of Santa Monica's daily water use. Once purified, the water is safe for all landscape irrigation and dual-plumbing systems as prescribed by the California Department of Health Services and meets California's Title 22 requirements.

Landscape irrigation customers include the Olympic Boulevard center median, some parks, and the City’s Woodlawn Cemetery. Recycled SMURFF water can be used in sites with overhead irrigation but only at night. Dual-plumbed customers include the City’s Public Safety Facility and commercial complexes, e.g. the Water Garden and the RAND Corporation. The SMURRF cost approximately $I2 million including the recycled water distribution system. The SMURRF is a multi-agency partnership built upon the regional benefits of the facility. Funding sources included the City of Santa Monica, the City of Los Angeles, the State Revolving Loan Fund, and two local and federal grants.

In summary, the City of Santa Monica has emerged as a leader in watershed management by recognizing and seizing the opportunities created by harvesting rain and dry weather runoff. While future potable water sources and treatment will continue to present challenges to urban infrastructures, cities can begin now to explore new ways to harness this precious resource before it all goes down the drain. This sustainable strategy will result in a cleaner beach, ocean and environment and a more reliable water supply for our communities and future generations to come.

Estimating Depth of Daily Rainfall Infiltrating the Soil Using the USDA-NRCS Curve Number Approach

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Abstract. *Estimating rainfall infiltrating into the soil (rainfall less runoff), is a key input to the checkbook method of irrigation scheduling. The checkbook method is a common tool for managing root zone soil moisture to maintain desired plant health and to conserve water.*

However, estimating infiltrated rainfall is fraught with uncertainty. It is strongly influenced by: rainfall (intensity, duration, amount), soils (texture, structure, bulk density, surface-sealing), land slope/ topography, antecedent soil water content, and plant cover (type, spatial extent, surface residue/mulch).

The USDA-NRCS curve number approach has been used for decades within hydrologic, soils, and water resources communities to estimate infiltrated rainfall. Required inputs include: daily rainfall depth, antecedent soil moisture, and selection of an appropriate curve number reflective of soil texture, land slope, and plant cover. Curve number values directly relate to depth of water intercepted by vegetation canopy and the soil surface before runoff occurs.

The curve number approach provides a reasonable balance between simplicity and accuracy to estimate depth of daily rainfall infiltrating soils. It is a significant improvement over use of a simple multiplier applied to measured rainfall or an algorithm based on a single factor such as rainfall intensity.

Keywords. Rainfall runoff, effective precipitation, irrigation scheduling, urban landscape water budgets, weather based irrigation controllers.

Background

When estimating rainfall infiltrating soils, it is common to first predict the expected runoff from measured rain. Surface runoff from rainfall is more easily observed and measured than the fraction of rainfall being infiltrated. Hence runoff algorithms can be readily supported by direct measurements in the field. Infiltrated runoff becomes the unmeasured remainder, and is calculated as measured rainfall minus runoff.

However, estimation of runoff from rainfall is fraught with uncertainty. Runoff during rainfall events is strongly influenced by multiple factors, including: soil texture, soil structure, sealing and crusting of the soil surface, vegetative cover, land slope, local land forming (tillage, furrowing, and ridging), antecedent soil moisture, and rainfall (intensity and duration/depth). Additional factors affecting effective precipitation are included in Table 2-42 of USDA-SCS Part 623 National Engineering Handbook, Chapter 2, Irrigation water Requirements.

The USDA-NRCS curve number approach utilizes characterizations of soil texture by the hydrologic soil groups described in Table 1.

Table 1. Hydrologic Soil Groups - from USDA-NRCS Part 630, National Engineering Handbook, Chapter 7, Hydrologic Soil Groups.

A	K_{sat} is generally greater than 1.42 iph. Water is transmitted freely through the soil. Typically have less than 10% clay and more than 90% sand or gravel, with more than 40 inches of soil above an impermeable layer or water table.
B coarse	K_{sat} is always generally between 0.57 iph and 1.42 iph. Water transmission is unimpeded through the soil. Typically have between 10%-20% clay and 50%-90% percent sand, with more than 40 inches of soil above an impermeable layer or water table. Loamy sand or sandy loam texture.
C medium	K_{sat} is generally between 0.06 iph and 0.57 iph. Water transmission is somewhat restricted through the soil. Typically between 20%-40% clay and less than 50% sand, with more than 40 inches of soil above an impermeable layer or water table. Loam, sandy clay loam, clay loam, and silty clay loam textures.
D fine	K_{sat} is generally less than 0.06 iph. Water movement is restricted or very restricted through the soil. Typically have greater than 40% clay and less than 50 percent sand, with more than 40 inches of soil above an impermeable layer or water table.

Procedures

Required data for using the USDA-NRCS curve number approach for estimating rainfall runoff are:

- daily precipitation depth.
- selection of appropriate CN (curve number) based on general soil, vegetation types, and land slope.
- AWC (antecedent soil water condition) - measured directly or computed from a daily soil water balance.

Table 2. Terms and Definitions.

P	Depth of rainfall during the event (inches).
CN	Curve number. Represents the relative imperviousness of the soil-vegetation complex and ranges from 0 for infinite perviousness and total infiltration to 100 for complete imperviousness and total runoff. Incorporates various factors effecting runoff, including land slope.

S = 10*(100/CN - 1)	Maximum depth of water that can be retained as infiltration and canopy interception during a single rainfall event (inches).
0.2*S	Rainfall intercepted by the vegetation canopy and soil surface before runoff occurs (inches).
$RO = (P - 0.2*S)^2 / (P + 0.8*S)$	Depth of surface runoff during the rain event (inches). RO = 0 when P<= 0.2*S and RO is always <= P
$P_{inf} = P - RO$	Depth of infiltrated rainfall (inches).
AWCI	Antecedent soil water condition for dry conditions, when watershed conditions are dry enough for satisfactory plowing or cultivation to take place.
AWCII	Antecedent soil water condition for average conditions.
AWCIII	Antecedent soil water condition for wet conditions, when watershed is practically saturated from antecedent rains.

If appropriate CN values are unknown, they can be approximated using the following algorithms. For AWCII (average soil water conditions), the CN values for fine soil textures can be calculated from observed values of 0.2*S, which is the depth of rainfall intercepted by the vegetation canopy and soil surface before runoff occurs. Once 0.2*S is determined, CN can be calculated as:

$$CN_{fine} = 100 / (0.2*S / 0.2 / 10 + 1)$$

For AWCII, the CN values for coarse and medium soil textures can be obtained from:

$$CN_{medium} = [(CN_{fine} - 47.2) / 0.5283] * 0.66 + 34$$

$$CN_{coarse} = [(CN_{fine} - 47.2) / 0.5283]$$

The CN values for AWCI and AWCIII, can be estimated from the corresponding CN for AWCII:

$$CN_{AWCI} = CN_{AWCII} / (2.281 - 0.01281 * CN_{AWCII})$$

$$CN_{AWCIII} = CN_{AWCII} / (0.427 + 0.00573 * CN_{AWCII})$$

When the actual AWC falls between AWCII and AWCIII, additional accuracy can be obtained by proportionally interpolating the CN values based on the value of AWC in relation to AWCII and AWCIII. This method can similarly be applied when AWC lies between AWCI and AWCII. This procedure was utilized by Allen and Robison, 2007.

Results

Tables 2a, 2b, and 2c include calculations of P_{inf} (rainfall infiltrated) for coarse, medium, and fine soil textures for a daily P (depth of measured rain) of 1.00 inches. Table 2a is for AWCI or dry antecedent soil water conditions, Table 2b is for AWCII or average antecedent soil water conditions, Table 2a is for AWCIII or wet antecedent soil water conditions.

Table 2a. Typical Values for Dry Antecedent Moisture Conditions

AWCI	Curve Number (CN)			P_{inf} for P=1.00 inches		
	Soil Texture			Soil Texture		
	Coarse	Medium	Fine	Coarse	Medium	Fine
Lawns, parks, golf courses, etc.	41	56	64	1.00	1.00	1.00
Bare urban soil - no vegetation	73	82	87	0.98	0.89	0.77
Suggested for urban landscape with 0 to 3% slope	62	73	78	1.00	0.98	0.94
Suggested for urban landscape with >3% to 6% slope	71	80	83	0.99	0.92	0.86
Suggested for urban landscape with >6% to 12% slope	77	84	87	0.95	0.84	0.77
Suggested for urban landscape with>13% slope	81	87	89	0.91	0.78	0.71

Table 2b. Typical Values for Average Antecedent Moisture Conditions

AWCII	Curve Number (CN)			P_{inf} for P=1.00 inches		
	Soil Texture			Soil Texture		
	Coarse	Medium	Fine	Coarse	Medium	Fine
Lawns, parks, golf courses, etc.	61	74	80	1.00	0.98	0.92
Bare urban soil - no vegetation	86	91	94	0.80	0.64	0.50
Suggested for urban landscape with 0 to 3% slope	79	86	89	0.93	0.80	0.72
Suggested for urban landscape with >3% to 6% slope	85	90	92	0.83	0.68	0.60
Suggested for urban landscape with >6% to 12% slope	89	92	94	0.73	0.58	0.50
Suggested for urban landscape with>13% slope	90	94	95	0.66	0.51	0.44

Table 2c. Typical Values for Wet Antecedent Moisture Conditions

AWCIII	Curve Number (CN)			P_{inf} for P=1.00 inches		
	Soil Texture			Soil Texture		
	Coarse	Medium	Fine	Coarse	Medium	Fine
Lawns, parks, golf courses, etc.	79	87	90	0.94	0.78	0.67
Bare urban soil - no vegetation	94	96	97	0.52	0.37	0.27
Suggested for urban landscape with 0 to 3% slope	90	94	95	0.68	0.52	0.44
Suggested for urban landscape with >3% to 6% slope	93	95	96	0.56	0.41	0.34
Suggested for urban landscape with >6% to 12% slope	95	97	97	0.45	0.32	0.27
Suggested for urban landscape with>13% slope	96	97	98	0.39	0.28	0.23

The values in Tables 2a, 2b, and 2c reflect significant differences of infiltrated rainfall due to varying soil textures, antecedent soil water conditions, and land slopes.

Conclusions

The curve number approach provides a reasonable balance between simplicity and accuracy to estimate the depth of daily rainfall that infiltrates the soil. Besides the measured rainfall depth, it incorporates additional key factors, including soil texture, vegetation/groundcover, land slope, and antecedent soil moisture conditions.

The use of the USDA-NRCS curve number approach would be expected to improve the accuracy of the checkbook method for irrigation scheduling, provide for improved landscape health, and promote conservation of water resources. It can readily be incorporated into landscape water budgets developed by developers or municipalities. Weather based irrigation controllers that utilized measured or estimated rainfall would similarly improve in their performance following significant rainfall events if adapted to incorporate the curve number approach for estimating effective rainfall.

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Wind Effects on Sprinkler Irrigation Performance

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Abstract. *Sprinkler efficiency, and implications on water waste, is often considered in terms of a single variable, such as minimum distribution uniformity or maximum precipitation rate. However, single variable metrics can be misleading. In addition, metrics, such as distribution uniformity, are measured in zero-wind buildings, which can inadvertently hide the extent to which efficiencies might decline when other variables are introduced, such as wind. The overarching objective of this study was to investigate a multi-variable approach to comparative sprinkler efficiency. The first objective of this study was to measure and analyze both distribution uniformity (DU) and application efficiency (AE) - total water caught in target zone divided by total water intended for target zone - versus wind speed across different nozzle designs. The second objective was to measure the distribution of the water droplet sizes for the same nozzles' sprays. Ultimately, the study was intended to determine if measureable trends emerged between the performance of the nozzles, given increasing wind speed, and their respective water droplet size distributions. During the testing, all nozzles' performance metrics declined with increasing wind – some were affected more than others. Compelling relationships emerged, illustrating a link between a sprinkler's water droplet size distribution and performance in terms of distribution uniformity and application efficiency.*

Keywords. sprinkler efficiency, distribution uniformity, DU, application efficiency, AE, wind speed, average water droplet size, water droplet distributions, The University of Arizona, zero-wind buildings, multi-variable sprinkler efficiency

Introduction

Emission device efficiency has been a focal point for legislative and regulatory actions to drive water conserving irrigation practices. From the EPA WaterSense New Homes Specification to California's Model Efficient Landscape Ordinance, similar standards have been adopted for minimum distribution uniformity and maximum allowable precipitation rates. Empirical evidence suggests that these standards have led to more efficient manufacturer solutions and, when used in conjunction with an integrated irrigation management approach, lead to reductions in water consumption.

Manufacturers, in support of these efforts, are striving to ensure their existing and new emission devices meet these tough regulations. Although there are independent agencies that can be used to verify subsets of legislative requirements; in many cases, manufacturers are left to test and self-certify that their sprinklers meet all requirements of a given legislation. However, most, if not all testing performed by manufactures is done indoors – in zero-wind conditions.

Relying on single variables to assess efficiencies – even comparatively between two emission devices –will not adequately indicate which product will perform more efficiently. Distribution uniformity and precipitation rate-only metrics, measured in zero-wind buildings, ignore water loss that will occur when wind pushes the spray pattern out of the target zone. The underlying assumption is that two different nozzles, if comparable at zero wind, will have reduced, but similar, degraded performance at any wind speed. To state it another way, if nozzle A's distribution uniformity and/or application efficiency is higher than nozzle B at a wind speed of zero, then at any wind speed, nozzle A's distribution uniformity and/or application efficiency will continue to be higher than nozzle B. The rationale is that both nozzles' performance will be reduced similarly.

Relying on single variables to assess efficiencies – even comparatively between two emission devices – often overstates that variable's effect on efficiency. As an example, Dukes et al. (2006) found that, "Although catch can measurements have been used for many years to quantify sprinkler irrigation application uniformity, it is clear that this method neglects the important process of water redistribution through the plant canopy, on the soil surface, and beneath the soil surface." The research concludes that the use of lower quarter distribution uniformity overstates the amount of water that needs to be applied to turf. This research points out that lower half, not lower quarter, is a closer approximate to soil moisture distribution uniformity. The research also illustrates a point in which an increase in catch can distribution uniformity does not translate into increased soil distribution uniformity, because the soil will distribute the water more evenly than a nozzle, sans sandy conditions. The authors also note that similar results have been reported by Mateos et al. (1997) and Stern and Bresler (1983) and Mecham (2001) on turfgrass. This indicates that there is too much emphasis on distribution uniformity scores, if distribution uniformity is used as a lone metric to indicate efficiency.

Given the objective of analyzing single efficiency metrics as wind was introduced, to determine the effects of varying wind speed on those metrics; our hypothesis was that all nozzles' efficiencies would decrease as wind speed increased, but the rate of decrease in performance would not be consistent across different nozzle designs. Further, we hypothesized that a relationship exists between the rate of decreased performance and average water droplet size, more specifically, the distribution of water droplet sizes making up a nozzle's spray pattern.

Methods

Efficiency Metrics vs. Wind Speed in Plot Testing

The following is excerpted from the final project report submitted by Karsten Turf Research Facility, The University of Arizona:

> The study was conducted at the University of Arizona Karsten Turf Research Facility located in Tucson, AZ. The Karsten Facility is located in the alluvial valley of the Rillito River at an elevation of 2440' above sea level. The specific experimental site consisted of eight 12'x12' blocks (plots) of Midiron Bermuda grass turf. Each plot has its own irrigation system complete with separate control valve and meter. Sprinklers are installed at the corners of each plot in a square spacing arrangement with adjacent heads separated by a distance of 12'. A total of 32 casings were installed in each plot to hold irrigation catch cups. All casings were installed to allow catch cups to be placed at turf level. Sixteen round casings constructed of 4" diameter PVC pipe were installed in a centered and evenly spaced square grid within the plot area. The separation distance between adjacent round casings was 3'. Sixteen rectangular casings constructed of short lengths of vinyl gutter were installed along the perimeter of the plot to facilitate collection of water applied to the edge of each plot. Catch cups were inserted into the casings prior to each irrigation run. The circular cups were the funnel-shaped cups manufactured by the CalPoly Irrigation Training and Research Center. Rectangular food storage containers (6"x 4.5"; Up and Up Brand) served as the perimeter catch cups.
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> The meters for each plot were calibrated at the beginning of the study and each time a different set of sprinklers were compared. The calibration procedure involved attaching a hose to one of the 2 irrigation risers while capping the remaining risers. The system was then operated for a set period of time with the water passing through the system collected in a large plastic carboy. The weight increase in the filled carboy was converted to volume units and then compared to the difference in meter readings obtained before and after each run. Meter adjustment factors were derived by dividing the volume collected during a run by the volume indicated by the meter.
>
> Each set of sprinkler heads was compared on a minimum of ten mornings during the summer of 2012 and winter of 2013. All sprinklers were installed in 4" Rain Bird Model 1800 SAMPRS bodies. Preliminary tests were conducted for each set of sprinklers to determine the precipitation rate. Run times were then set such that each set of heads applied approximately 0.50" of water. For a given comparison event, irrigation of all plots (both sprinklers) was initiated at the same time. The termination time of irrigation varied due to the differences in precipitation rate of the opposing sprinklers. At the completion of each run, the volume of water in each cup was determined by transferring the water collected into a graduated cylinder and recording the resulting volume. Catch

cup volumes were then converted to depth by dividing by the surface area of the cup. All comparisons were run during the morning hours in the summer of 2012. Some afternoon comparisons were included in the winter of 2013 to avoid subfreezing conditions and to better assess the performance of the sprinklers during periods with higher wind speeds.

Sprinkler performance was evaluated by measuring distribution uniformity (DU) and application efficiency (AE). Distribution uniformity was computed using the 16 circular catch cups located within each plot. Specific DU computations included the low quarter distribution uniformity (LQDU) and low half distribution uniformity (LHDU). The LQDU is determined by computing the average of the lowest 25% of catch volumes (depths) then dividing this value by the average volume (depth) of all cups. The LHDU is determined by computing the average of the lowest 50% of catch volumes (depths) then dividing this value by the average volume (depth) of all cups. The scheduling coefficient (SC) was also computed for each comparison using the 16 circular catch cups. The SC was computed by dividing the average depth of water collected in the 16 catch cups by the smallest depth of water collected in a single cup (of 16 catch cups).

Application efficiency was determined using two difference computation procedures. The first procedure (AE16) involved taking the average depth of the 16 circular catch cups and dividing by the equivalent depth of water that passed through the water meter (meter volume converted to depth based on plot area of 144 sq. ft.). The second computation procedure (AE32) used all 32 catch cups to estimate the depth of water reaching the turf surface. In this procedure the total area of the plot was divided into 21 rectangular areas with catch cups located at the four corners of each area (Fig. 2). The average depth of water applied to each rectangle was computed by taking the average of the four corner catch cups. The four small corner areas of the plot had just three catch cups since the sprinkler head was located on the fourth corner (Fig. 2). For these corners, the depth of water collected at the head was estimated by averaging the catch values of the two closest cups. This estimated value was then averaged with the three cup values to estimate the depth of water received in the small corners. Depth estimates for the 25 rectangles were then multiplied by their respective areas (9, 4.5 or 2.25 sq. ft.), summed and divided by the total plot area (144 sq. ft.) to obtain the average amount of water reaching the plot surface. This value was then divided by the actual depth of water applied (as determined from the meter) to determine AE32.

Experimental design was randomized complete block with two treatments (irrigation heads) and four reps. All data were analyzed using the appropriate statistical procedure as provided by SAS (SAS Institute, Cary, NC).

A weather station was installed upwind of the plots to provide data on temperature, humidity, wind speed and wind direction during each evaluation period. Temperature and humidity were monitored at 5' (1.5 m) above ground level (agl) with a Vaisala Model HMP45C combination temperature and relative humidity sensor. Wind speed and direction were monitored at 6.6' (2.0 m) agl using a RM Young Model 03002Wind Sentry Set. All sensors were connected to a Campbell Scientific Inc. 4 Model 10X datalogger programmed to scan sensors at 0.2 Hz and output parameter means every 15 sec. The meteorological data were downloaded to a portable computer then imported into spreadsheet software where the data were summarized over the specific run times of each evaluation.

Nozzle's Water Droplet Distribution Testing

The following is excerpted from the final project report submitted by Spraying Systems Company, Spray Analysis and Research Services group:

> The Sympatec HELOS Particle Analyzer was used to acquire drop size measurements for this test. The Sympatec is a laser diffraction instrument that measures drop size based on the energy of the diffracted light caused by drops passing through the analyzer's sampling area. The Sympatec uses a 632.8nm HeNe-laser with a long resonator. The scattered light intensity distribution is measured using a multi-element semicircular photo-detector housed in the receiver unit. Testing was performed using a R6 and R7 lens setup. These lens configurations allow a measurement range of 9.0 µm to 1750 µm and 18.0 µm to 3500 µm respectively.
>
> The spray head and nozzles were attached to the platform of a lift truck, which allowed for the entire spray plume to be passed through the measurement zone [vertically] at a specified [1 foot, 3 feet, 6 feet] horizontal distance. The water pressure [30 psi, 50 psi, 70 psi] was controlled by an adjustable needle valve and monitored using an analog Bourdon Tube pressure gauge. A cylinder with approximately a two inch wide cut along its length was lined with a mist eliminating pad, which was used to block most of the stream and only allow a narrow section to pass through the measurement zone of the analyzer. The mist eliminating pad prevented splashing of the spray inside the cylinder from interfering with the testing portion of the spray pattern.
>
> Drop size distribution is expressed by the particle size versus the cumulative volume percent, as all drops within a given spray plume are not the same size. Smaller droplets possess greater drift potential. These drops have less momentum than larger droplets and are more likely to drift off or evaporate as they move further away from the nozzle orifice. As the MVD (DV0.5) is the average volume of all the droplets present in the sample, the presence of larger droplets significantly influences the resultant MVD value.

> All drop size measurements were taken at the same distances for nozzles of the same type […]. The spray plume was scanned a minimum of three times, […], and straight averaged to obtain the final cumulative drop size values and cumulative distribution graphs.

Attention should be brought to this last point. A minimum of three scans were taken for each pressure and distance point. In cases where the first three scans did not show consistency in measurements, additional scans were obtained to ensure consistent results. Inconsistent results were often the result of water droplets getting onto the measuring device's lens, which would create results that were easily distinguishable as an invalid scan.

Results and Discussion

Efficiency Metrics vs. Wind Speed in Plot Testing

Table 1 shows a summary of results obtained during both summer and winter trials of Nozzle B versus Nozzle C. A range of significantly different values were obtained as measured by the catch can method. It is apparent that wind speed during individual comparison events greatly impacted the comparative results in all four measurements. Nozzle B produced significantly higher values in all four metrics, as compared to Nozzle C, regardless of the season.

Table 1 Average of Metrics (B versus C)

Summer Trials				
Wind Speed Range	0 – 9.2 mph			
Wind Speed Average	3.6 mph			
	LQDU	**LHDU**	**AE(16)**	**AE(32)**
Nozzle B	52%	72%	81%	78%
Nozzle C	40%	64%	62%	60%
Stat Sig ($p<0.05$)	Yes	Yes	Yes	Yes
Winter Trials				
Wind Speed Range	1.1 – 5.1 mph			
Wind Speed Average	3.1 mph			
	LQDU	**LHDU**	**AE(16)**	**AE(32)**
Nozzle B	75%	85%	77%	79%
Nozzle C	65%	80%	75%	72%
Stat Sig ($p<0.05$)	Yes	Yes	Yes	Yes

The researchers noted in their report that Nozzle C appeared to produce smaller droplet sizes in comparison to Nozzle B and was more vulnerable to drift under moderate to high wind conditions – which is confirmed in the data. The lower values of AE(16) and AE(32) for Nozzle C provide clear evidence that a significant amount of water simply drifted out of the target zones.

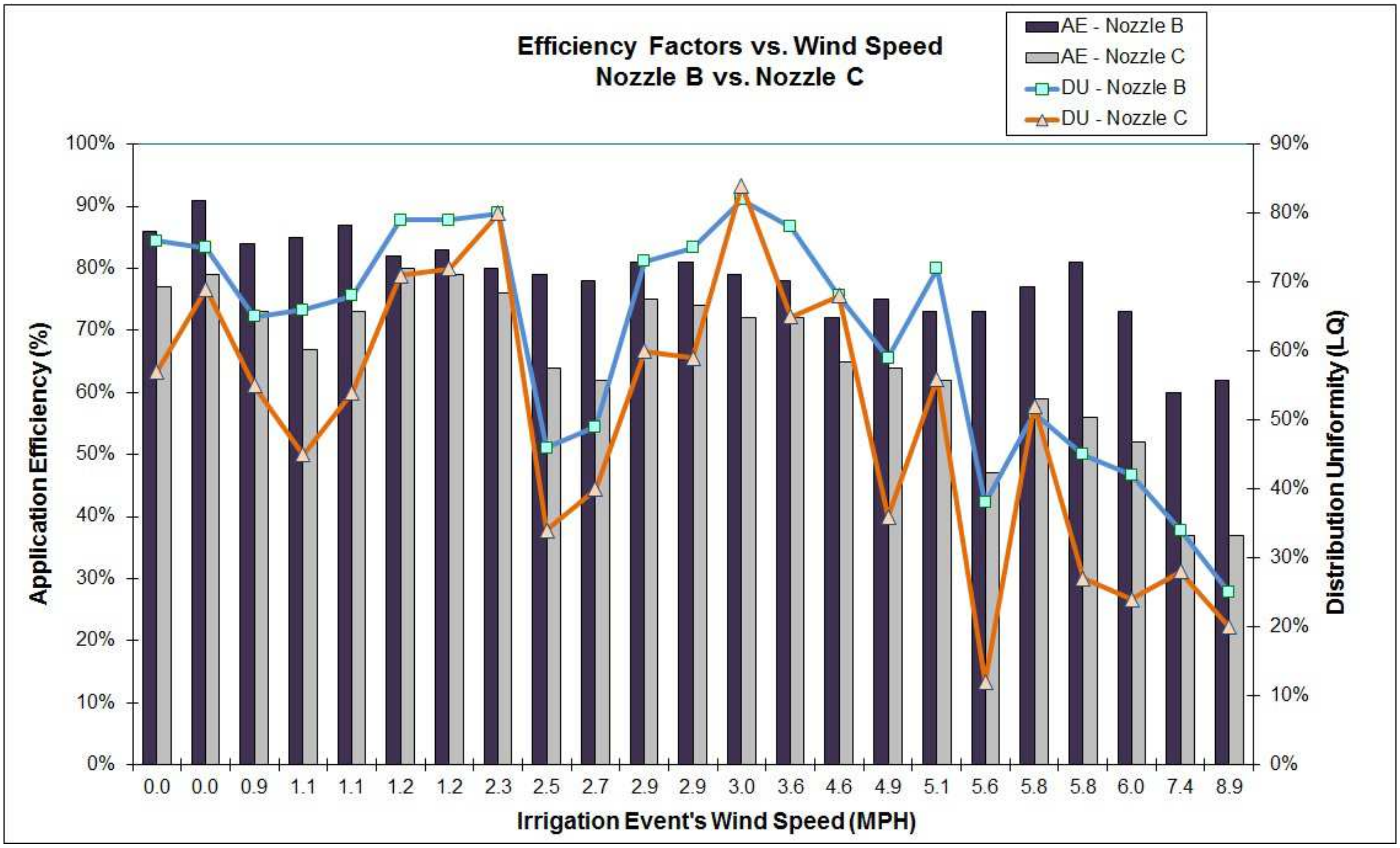
The researchers also noted that the depth of water collected was significantly lower in plots irrigated with Nozzle C – even though all plots received 0.50 inch of water.

Although separating water loss into drift and evaporation components was not within the scope of this study, the researchers noted in their final report an interesting trend they uncovered in the data and provided a hypothesis for consideration:

> It is interesting to note that the relationship between perimeter catch and wind speed appear to differ from summer to winter as do several other performance parameters. One possible explanation for this difference could rest in the evaporative potential of the atmosphere. Vapor pressure deficit (VPD), a measure of the difference from saturation of the water vapor pressure in the atmosphere, represents the best means of estimating the evaporative power of the air. The VPD during the summer and winter comparisons averaged 2.98 kPa and 0.87 kPa, respectively. One should expect the higher VPDs in summer to produce more spray evaporation during irrigation events with the overall effects greatest in plots irrigated with [Nozzle C] due to the much smaller droplet size. The differing response of [Nozzle C] to wind speed […] support the evaporation hypothesis. It is also interesting to note the improvements in AE16 and AE32 for [Nozzle C] in winter as compared to summer. Considerably more water was reaching the catch cans in winter relative to summer, again suggesting [Nozzle C] is more prone to evaporation due to the smaller droplet size. A similar response was not observed from plots irrigated with [Nozzle B] which produce larger droplets and should be less prone to evaporation.

Graph 1 shows individual irrigation event results for application efficiency and lower quarter distribution uniformity. The data is sorted by wind speed to provide a perspective for the rate of decline of these efficiency metrics as wind speed increases.

Graph 1 Efficiency Factors vs. Wind Speed (B versus C)



The data clearly illustrates that both of these nozzles' performance experienced a decline as wind speed increased, which was expected. Looking at the data in this manner exposes two areas for consideration. First, LQDU values for both nozzles appear to trend together in their decline with increasing wind speed. However, looking at application efficiency, it is clear there is a tipping point for Nozzle C around 4 MPH, where Nozzle C's rate of decline increases as compared to Nozzle B. In this case, given a single view of LQDU, one might conclude the nozzles are comparable, given discussions of data collection and measurement limitations. However, in this case, if one was provided application efficiency versus wind speed, a clear distinction of efficiency becomes apparent, as Nozzle B is clearly able to provide more water into the target zone as wind speed increases.

Table 2 shows a summary of results obtained during both summer and winter trials of Nozzle A versus Nozzle C. A range of significantly different values were obtained, with the exception of LHDU during the summer trials, as measured by the catch can method. This evaluation produced mixed results.

Table 2 Average of Metrics (A versus C)

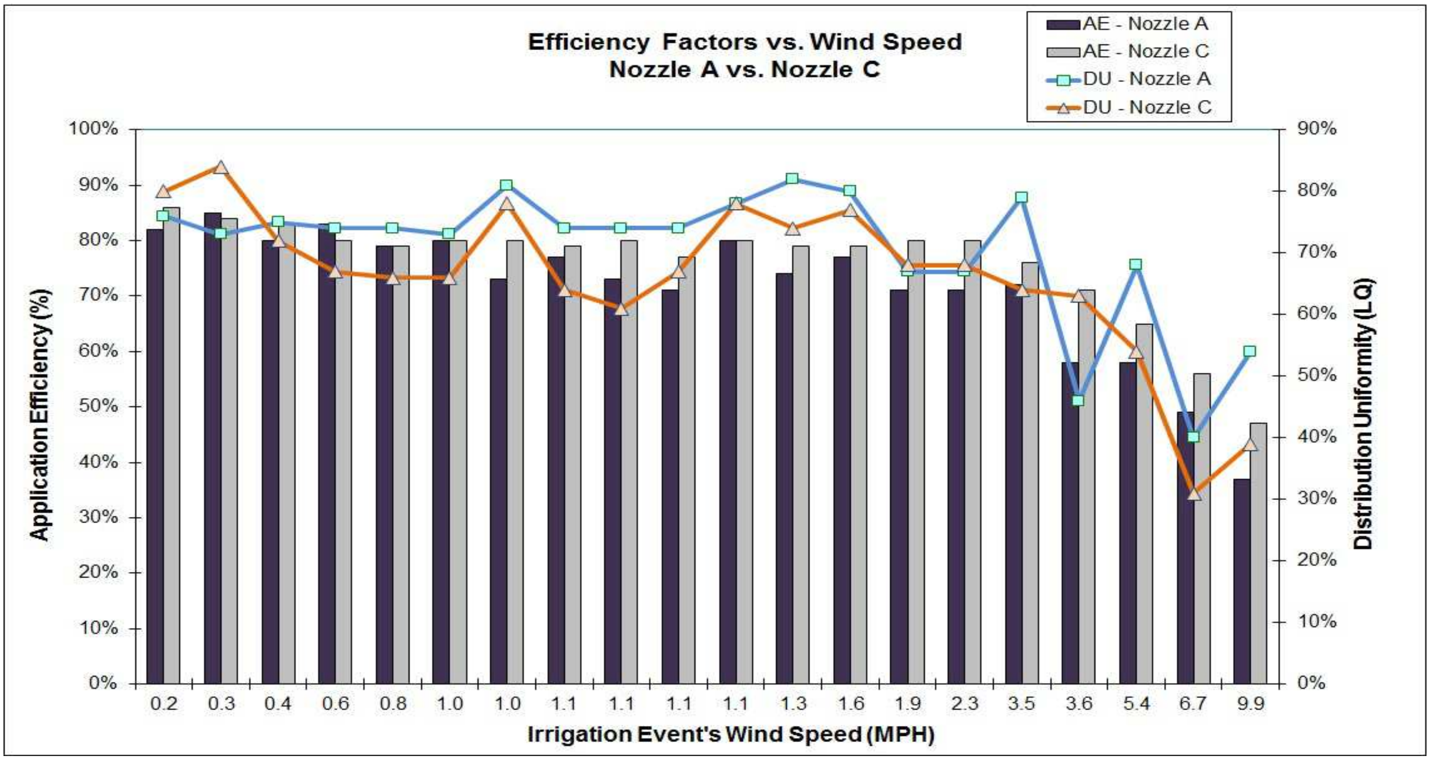
Summer Trials				
Wind Speed Range	0 – 2.5 mph			
Wind Speed Average	1.6 mph			
	LQDU	**LHDU**	**AE(16)**	**AE(32)**
Nozzle A	**75%**	82%	75%	81%
Nozzle C	**70%**	82%	85%	78%
Stat Sig (p<0.05)	Yes	No	Yes	Yes
Winter Trials				
Wind Speed Range	1.1 – 9.8 mph			
Wind Speed Average	3.7 mph			
	LQDU	**LHDU**	**AE(16)**	**AE(32)**
Nozzle A	66%	79%	61%	65%
Nozzle C	62%	77%	74%	71%
Stat Sig (p<0.05)	Yes	Yes	Yes	Yes

The impact of wind on sprinkler performance was again evident in this analysis, as can be seen in the decline in metrics from summer to winter trials, which experienced higher winds. Wind negatively impacted both LQDU and LHDU on both nozzles. In some cases, legislation today has us compare LQDU values alone to determine which nozzle is more efficient. Unfortunately, most of the available data to make the comparison has been collected in zero wind conditions. Taking a look at the bolded summer trial's LQDU data – which had very low wind (0 – 2.5 mph) and would closely approximate indoor testing results – one would conclude that Nozzle A is more efficient than Nozzle C.

However, provided more information, as presented in Table 2, one would not be able to conclude determinately which nozzle to be more efficient. One could argue that given this set of data, looking at AE(16) and AE(32) during the winter trials, that Nozzle C is capable of providing more water into the target zone at higher wind speeds. Therefore, selecting Nozzle C will result in higher efficiency due to its ability to provide greater wind protection – delivering more water into the target zone and allowing the soil to provide further distribution of the water in the soil, as supported by Dukes et al. (2006) discussed previously. This supports the concern of overemphasis of any one variable as a determinate of efficiency.

Graph 2 shows the individual irrigation event results for application efficiency and lower quarter distribution uniformity. The data is sorted by wind speed to provide a perspective for the rate of decline of these efficiency metrics as wind speed increases. Looking at the complete set of data in this fashion, as the researchers pointed out, "A clear advantage did not emerge from the evaluations comparing [Nozzle A] to [Nozzle C]." This conclusion was reached because neither nozzle provided a clear advantage in any of the four metrics, when comparing both LQDU and AE.

Graph 2 Efficiency Factors vs. Wind Speed (A versus C)

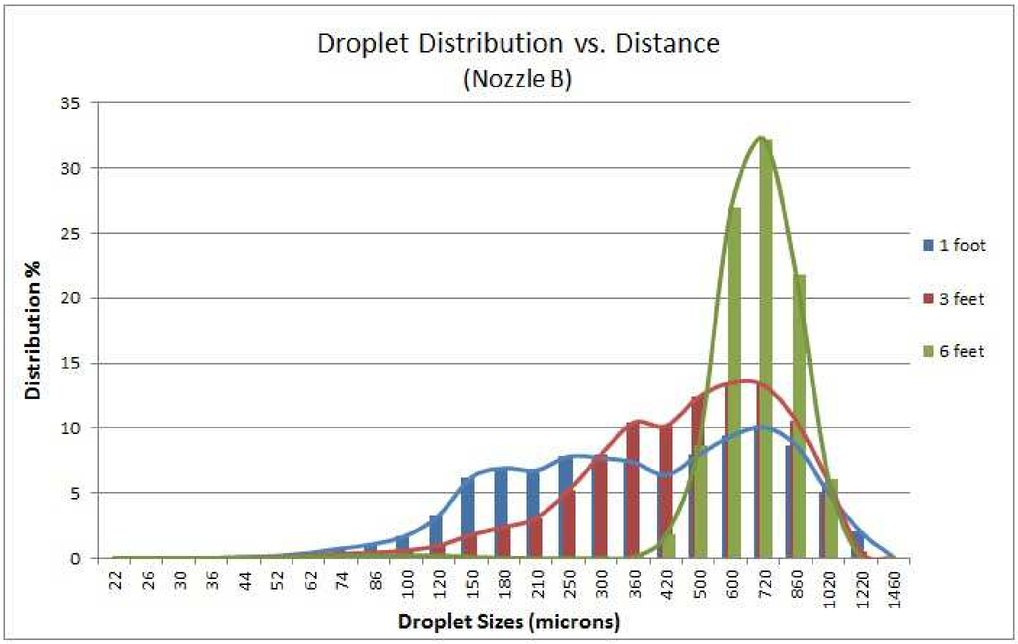


<u>Nozzle's Water Droplet Distribution Testing</u>

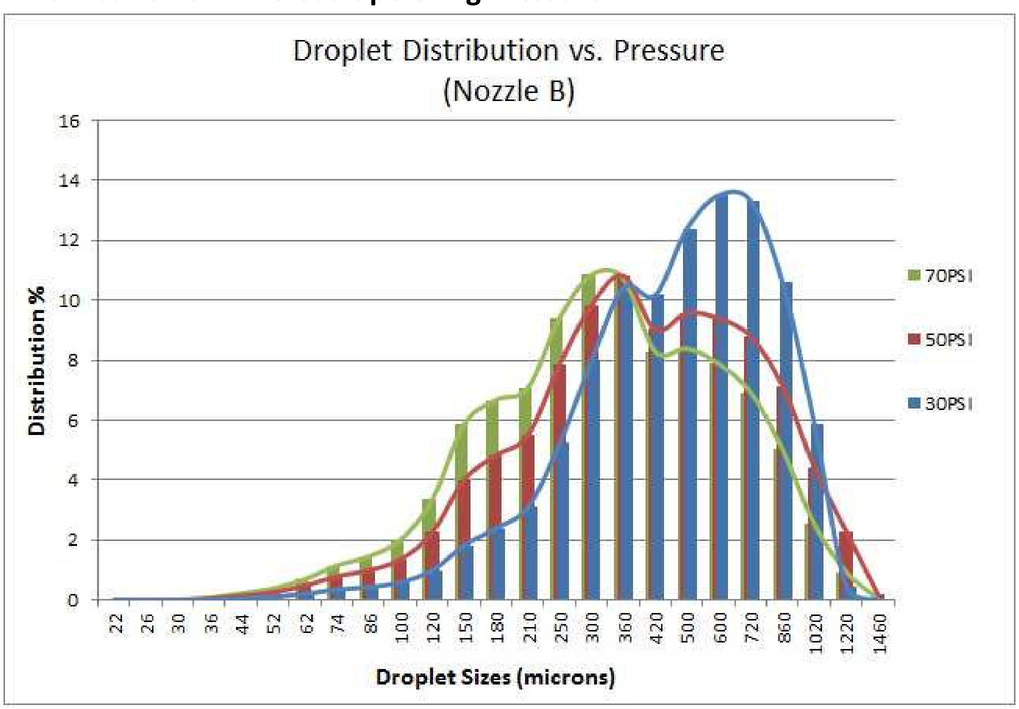
Prior to comparing measured values of each nozzle, it was desirable to ensure expected trends emerged within each nozzle's data. It would be expected that if measurements were made close to the nozzle's orifice and then further away horizontally, closer measurements would contain a higher percentage of smaller water droplet particles. Measurements taken further from the nozzle should contain a higher concentration of larger water droplets because smaller droplets should have drifted (or evaporated) away. Second, it would be expected that significant differences in measurements should be seen as pressure increases. As pressure increases, water should atomize and create a higher concentration of smaller water particles.

It was determined all nozzles would be measured at 1 foot, 3 feet, and 6 feet measurements, horizontally from the nozzle. In addition, at each horizontal location, measurements would be taken at 30 psi, 50 psi, and 70 psi. The expected trends as described are significant in each nozzle's data. Graph 3 and graph 4 are provided to illustrate the existence of the trends captured on Nozzle B. Although pressure regulation was not within the scope of this project, graph 4 provides strong implications regarding the reduction of water lost through evaporation and drift when pressure regulation is installed in high pressure situations. Graph 4 provides strong evidence that high pressure causes smaller water droplets that will increase water loss significantly.

Graph 3 Distribution Shift versus Distance from Sprinkler



Graph 4 Distribution Shift versus Operating Pressure

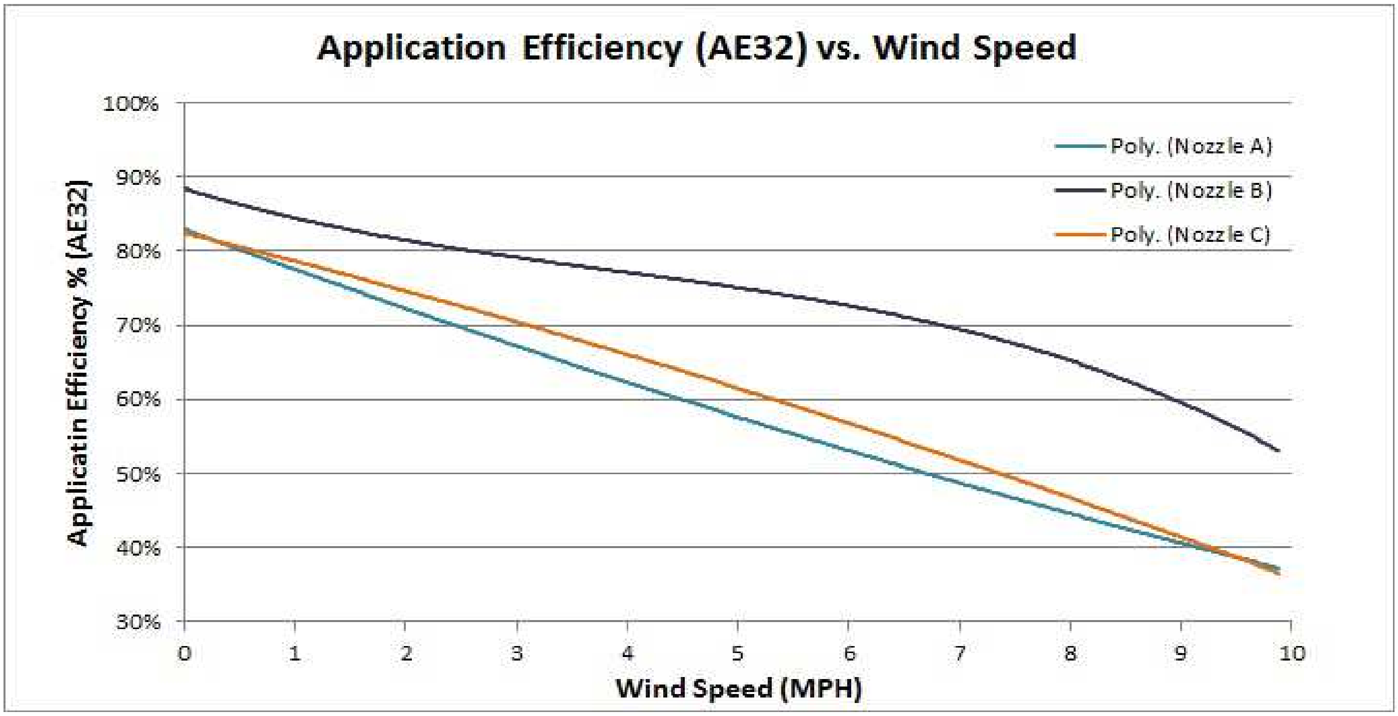


Tying the Research Together

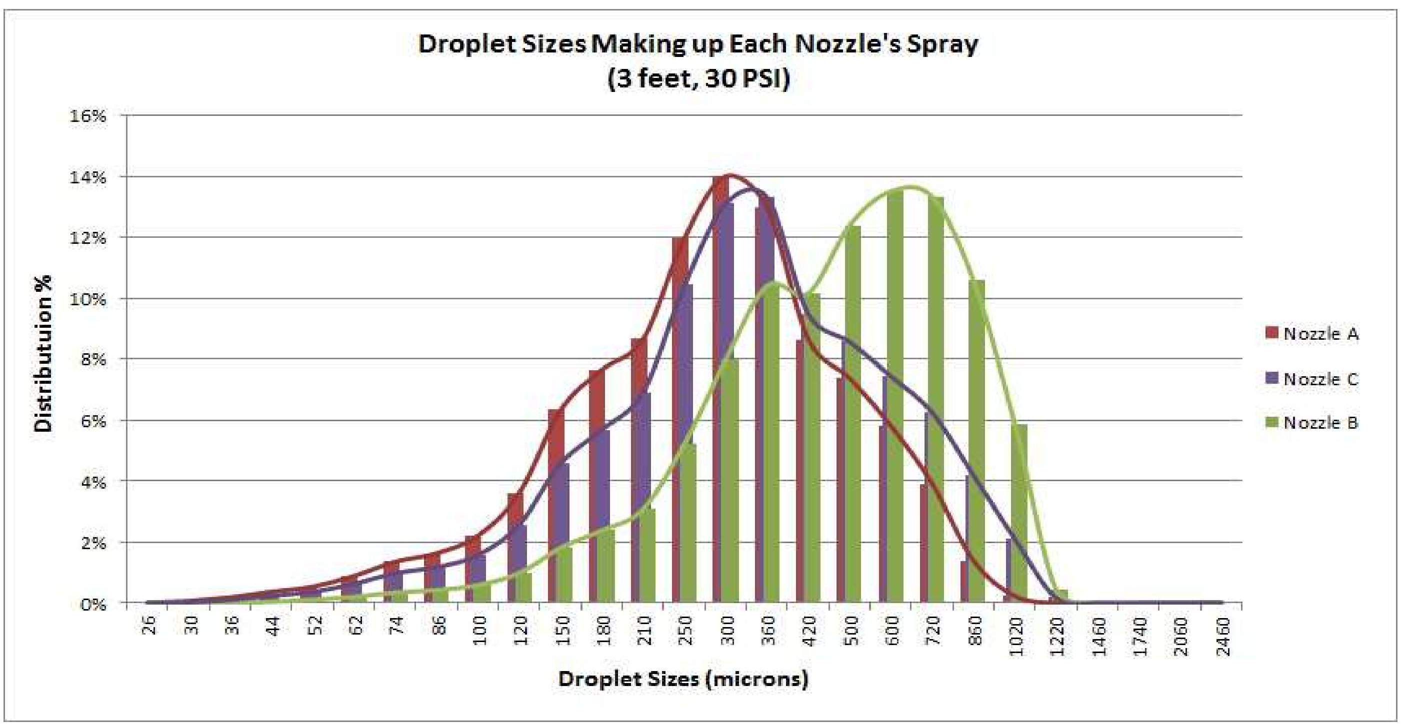
At the outset of this project the primary objective was to determine if efficiency metrics could be plotted against wind. In essence, the objective was to generate more accurate pictures of differing nozzle designs' efficiencies when operated in their actual environments. Over the course of time during the work at The University of Arizona, it became apparent that testing nozzles outdoors for extended periods of time to generate statistically relevant curves is not practical. This led to the second objective, which was to identify a possible solution for overcoming the impractical nature of testing outdoors, yet still being able to generate the data. Hence, the second portion was initiated to take the same nozzles and attempt to measure their water droplet size distribution curves. In this, it was important to ensure the results were repeatable and that the measurements followed trends provided by a general understanding of physics. It has been determined that the results of droplet testing are repeatable. It has been determined that the results of droplet testing follow expectations set forth by a general understanding of physics, regarding distance of measurement and pressure variations. This is all somewhat academic, as other industries have utilized this type of measurement for many years and use the results to develop different nozzle technologies. The American Society for Testing and Materials (ASTM) has well defined standards for measuring particle sizes.

Graph 5 shows the best fit trend lines for each nozzle versus wind speed as determined by The University of Arizona research team. Evident in this graph is that there is something fundamentally different about Nozzle B that allows it to get a higher percentage of water into the target zone as wind speed increases, compared to the other two nozzles. The primary hypothesis is that the attribute is larger average water droplet sizes. Graph 6 confirms the hypothesis.

Graph 5 Trend Lines of Application Efficiency vs. Wind Speed

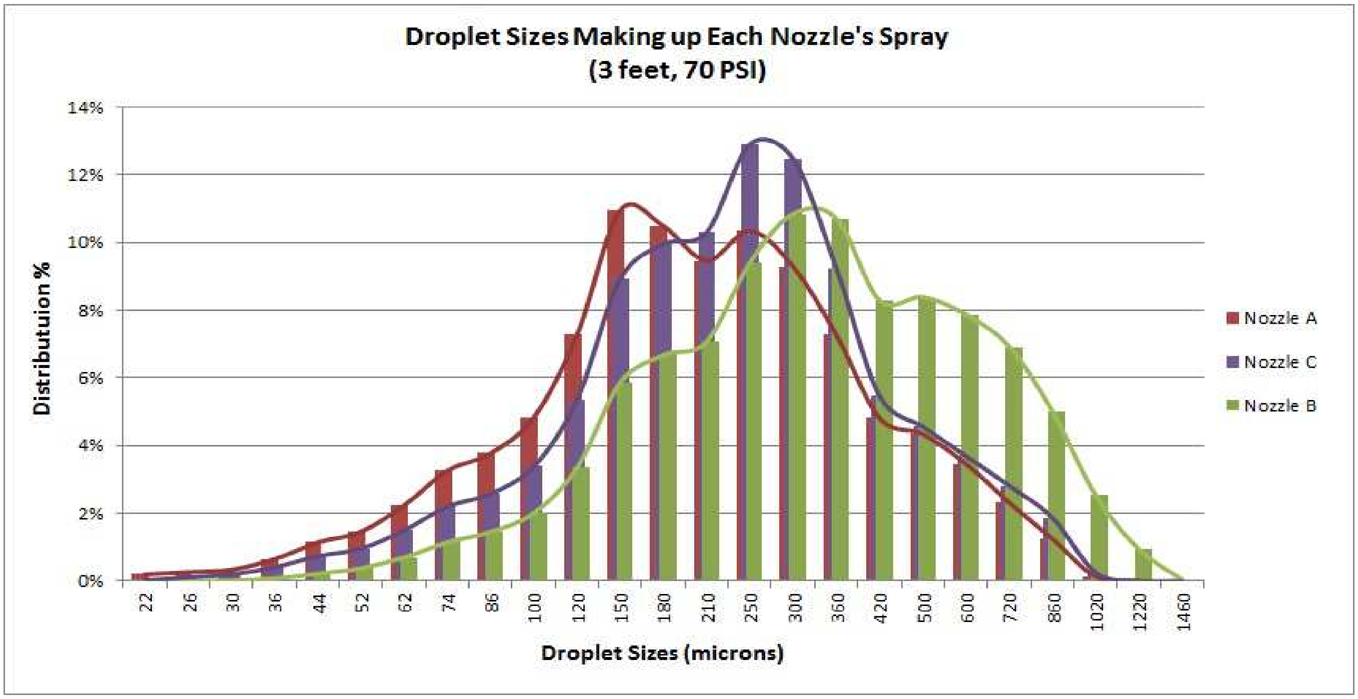


Graph 6 Nozzle Spray Make Up at 3 Feet and 30 PSI



Although not in the original scope of the research, the data that was collected also illustrates that nozzles designed with a spray made up of larger water droplets are able to tolerate higher pressures. This seems logical because it would take higher pressure to atomize larger water droplets.

Graph 7 Nozzle Spray Make Up at 3 Feet and 70 PSI



Conclusions

Although single metrics have been used for years to quantify an emissions device's efficiency factor, it is clear that any single data point metric can be troublesome when relied on solely to compare two devices. A multi-variant approach to quantifying a sprinkler's efficiency, including efficiency metrics versus wind speed, is a step towards a more complete picture of a sprinkler's efficiency.

Despite the testing of only 4 different nozzles, with limited data sets, compelling trends between efficiency factors versus wind speed and water droplet size distribution emerged. This is encouraging and indicates more data should be collected and analyzed to find stronger correlations between wind curves and water droplet size distributions. This could eventually lead to the ability to simply measure a sprinkler's resulting water droplet size distribution and very closely approximate the resulting distribution uniformity and application efficiency as a function of wind speed – removing the need to test product outside for extended periods.

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Benchmarking System Efficiency within Orange County, California

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Abstract. *Excessive outdoor water use results from system inefficiency and poor management. The average water savings potential within Orange County, CA will be benchmarked by examining a sub-sample of water use of approximately 50,000 single family residences, along with six program evaluations. Water budgets (theoretical irrigation need) have been calculated for each meter with respect to weather data. Pre/post implementation comparisons can be made by cross referencing the rebate program database. Examination of "well-maintained" systems will benchmark realistic system efficiency goals. Using predictive ellipses to forecast the water savings of timer rebate program yields a potential for 5% to 11% of total household use at 95% confidence. This analysis suggests that the potential for water savings from management is minimized when the system has greater inefficiencies, and air temperature resulted in the strongest predictive variable of irrigation trends.*

Keywords. *Residential landscape irrigation, Commercial landscape irrigation, Weather-based irrigation controllers, system efficiency*

Introduction

Irrigation is required to maintain outdoor landscapes in Orange County, California. Orange County has a Mediterranean climate: a semi-arid environment with mild winters, warm summers, and moderate rainfall. The climate is semi-arid and consistent with coastal Southern California. The general region lies in the semi-permanent high-pressure zone of the eastern Pacific. As a result, the climate is mild, tempered by cool sea breezes. The usually mild climatological pattern is interrupted infrequently by periods of extremely hot weather, winter storms, or Santa Ana winds.

IN a typical year, Orange County’s average daily temperatures range from 58˚F in December and January to 74˚F in August. The average annual precipitation is 14 inches, although the region is subject to significant variations in annual precipitation. The average evapotranspiration (ET_O) is almost 50 inches per year, which is four times the annual average rainfall. This translates to a high demand for landscape irrigation for homes, commercial properties, parks, and golf courses. A region with low rainfall, like Southern California, is also more prone to droughts.

The Municipal Water District of Orange County (MWDOC) is a regional water wholesaler and resource planning agency managing all of Orange County's imported water supply with the exception of water imported to the cities of Anaheim, Fullerton, and Santa Ana. MWDOC serves more than 2.3 million residents in a 600-square-mile service area. MWDOC implements landscape water use efficiency programs that target excessive outdoor water use resulting from system inefficiency and poor management. Landscape water use efficiency is a priority in Orange County as nearly half the water supply is imported and the region is vulnerable to water shortages.

This paper involves two analyses aimed at benchmarking system efficiency and savings potential within Orange County. The first performs a meta-analysis of program evaluations for MWDOC landscape water use efficiency programs to test the hypothesis that the installation of new irrigation technology or better management of equipment would reduce the observed water consumption for participating customers. The second is an examination of the landscape water use of “well-maintained” systems to benchmark realistic system efficiency goals.

Data and Methods

Meta Analysis of Program Evaluations

Since 2001, MWDOC has been providing incentives for the installation of weather-based irrigation controllers (smart timers) at residential and commercial properties, through either standard rebates or direct installs programs, all with 100% post-installation inspections. These programs have been evaluated through six independent studies following a similar water savings analysis approach (Hunt et al. 2001; Bamezai 2001; A&N Technical 2004; A&N Technical 2006; Kennedy Jenks Consultants 2008; A&N Technical 2011).

To complete a meta-analysis of these studies, results from approximately 10,000 consumption records were compiled from the retail agency billing systems for customers in these study areas. Billing histories were obtained from meter reads between 2001 and 2011. Since the number of days contained in a meter read can vary, the analysis converted customer water consumption to average daily values in a meter read period to standardize use across varying lengths of meter read periods. Observed water consumption was statistically controlled for weather and customer/site heterogeneity.

Since installation of smart timers (weather-based irrigation controllers) through a county-wide rebate program requires the voluntary agreement of the customer to participate, these sample of customers can be termed “self-selected.” While this analysis does quantitatively estimate the reduction of participant’s water consumption, one may not directly extrapolate this finding to non-participants. This is because self-selected participants can differ from customers that decided not to participate.

Daily weather measurements - daily precipitation, maximum air temperature, and evapotranspiration - were collected from the National Oceanographic and Atmospheric Administration Weather Service Office weather stations located in Orange county, the California Irrigation Management Information System (CIMIS) station No. 75, and Irvine Ranch Water District (IRWD) weather stations. Additionally, the previously evaluated CIMIS spatial interpolations of evapotranspiration data were developed for each participating agency. Additional weather zones specified for IRWD - inland, middle, and coastal - with customer accounts were assigned to one of the three Spatial ET_o measures on the basis of zipcode. This “Spatial ET_o” was statistically tested against nonlocal ET_o measurements. The daily weather histories for rainfall and temperature were collected as far back as were available (January 1, 1948 for NOAA stations) to provide the best possible estimates for “normal” weather through the year. Thus we have at least 63 observations upon which to judge what “normal” rainfall and temperature for January 1^{st} of any given year. CIMIS Spatial ET_o measures were available back to 2004. Rolling monthly and bimonthly averages of rainfall, temperature, and evapotranspiration were created to exactly match to meter read dates for all customer water consumption histories.

Robust regression techniques were used to detect which observations are potentially data quality errors. This methodology uses a given model fro to determine the relative level of inconsistency of each observation. A measure is constructed to depict the level of inconsistency between zero and one; this measure is then used as a weight in subsequent regressions. Less consistent observations are down-weighted. Other model-based outlier diagnostics were also employed to screen the data for any egregious data quality issues. Interviews with conservation staff and site visits were conducted to track down and confirm data quality issues.

Benchmark of Water Savings Potential

To benchmark the water savings potential of existing outdoor landscapes, research is being conducted to determine whether single-family household residents adjust landscape irrigation based on climate or income in Orange County, California. Specifically, the goal of this research is to (1) determine the amount of over- or under-irrigation compared to theoretical need and (2) determine the climatic and socio-economic controls on landscape irrigation. A research partnership was established between six water retail agencies in Orange County: City of Huntington Beach, El Toro Water District, Irvine Ranch Water District, East Orange County Water District, City of San Juan Capistrano, and Laguna Beach County Water District. These agencies represented a wide range of climatic and economic conditions of single-family residential water use data on a monthly/bimonthly basis.

Using information from this ongoing research, data from 50,000 accounts on household water use, climate, and socioeconomic factors were mapped using Arcview GIS. A multiple regression of single-family residential water use was conducted with air temperature (California Irrigation Management Information System), precipitation (Orange County ALERT Precipitation Network), and household income (US Census) as possible explanatory variables.

The theoretical irrigation demand is calculated by subtracting the amount of effective precipitation from the landscape water need. The landscape water need is calculated with the following equation:

$$\text{Landscape Water Need} = \frac{ET_o \times k_{c-turf} \times A_{turf}}{IE_{turf}} + \frac{ET_o \times k_{c-shrub} \times A_{shrub}}{IE_{shrub}} + ET_o \times k_{c-pool} \times A_{pool}$$

Where,

ET_O = evapotranspiration (inches/month)
k_c = crop/pool coefficient
A = fraction of area (%)
IE = irrigation efficiency (%)

The average landscape coefficients used were: 0.8 for turfgrass (varied by month), 0.5 for ornamental/shrub areas, and 1.0 for pools.

Three million rows of household level water use data were analyzed. Outdoor water use was estimated using the "minimum month method". The volume of outdoor water use was then divided by area to obtain depth of irrigation. Area measurements were obtained from National Agriculture Imagery Program 2009 land areas, where the total average error on these areas is 7.5% (Mende and Norris 2010). Sixty seven percent of the IRWD service area sample (n = 34,116 of the 50,950 single-family residences) were matched and presented here. Additionally, monthly outliers greater than five standard deviations above the annual mean for a single-family residences were removed. Inclusion of this data would have skewed the results. Low-end outliers were not removed, as they may be representative.

Results

Meta Analysis of Program Evaluation

Table 1 summarizes the findings of six independent evaluations of programs conducted by MWDOC on residential and commercial weather-based irrigation controller programs. Table 1 lists the study title, evaluation consultant, and water savings for each study. Figures 1 and 2 illustrate the water savings from these study areas as percentages of overall water use, and net water savings from each of the studies listed in Table 1.

The standard ellipse used in Figures 1 and 2 is a descriptive tool; it is used to visualize the variability of individual samples. The standard ellipse serves the same purpose as the standard interval mean, +/- standard deviation in univariate statistics. The prediction interval ellipse describes the area in which a single new observation can be expected to fall with a certain probability (i.e. 95% confidence), given that the new observation becomes a distribution with the parameters (means, standard deviations, covariance) as estimated from the observed points shown in the plot. For residential sites, the predictive ellipses allude to a potential water savings of 5% to 11%, with 95% confidence, and between 29 and 54 gallons per day per household. For commercial sites, the predictive ellipses depict that a potential water savings has a much broader range, -6% up to 40%, with 95% confidence, and between approximately 400 and 800 gallons per day per site.

Table 1. Compilation of MWDOC's weather-based irrigation controller program evaluations.

<table>
<tr><th>Study Title</th><th>Year</th><th>Author</th><th>Sector</th><th>Water Savings per WBIC[Z] (gal/day)</th><th>Retrofit Accounts in Study (#)</th><th>Total Water Use (%)</th><th>Landscape Water Use (%)</th></tr>
<tr><td>Residential Weather-Based Irrigation Scheduling: Evidence from the Irvine "ET Controller" Study</td><td>2001</td><td>Hunt et al.</td><td>Residential</td><td>37</td><td>40</td><td>7%</td><td>16%</td></tr>
<tr><td>ET Controller Savings Through the Second Post-Retrofit Year: A Brief Update</td><td>2001</td><td>Western Policy Research</td><td>Residential</td><td>41</td><td>40</td><td>8%</td><td>18%</td></tr>
<tr><td rowspan="2">Residential Runoff Reduction Study</td><td rowspan="2">2004</td><td rowspan="2">A&N Technical Services, Inc.</td><td>Residential</td><td>41</td><td>112</td><td>10%</td><td>-</td></tr>
<tr><td>Commercial</td><td>545</td><td>26</td><td colspan="2">21%[Y]</td></tr>
<tr><td>Commercial ET-Based Irrigation Controller Water Savings Study</td><td>2006</td><td>A&N Technical Services, Inc.</td><td>Commercial</td><td>601</td><td>-</td><td colspan="2">22%</td></tr>
<tr><td rowspan="2">Pilot Implementation of Smart Controllers: Water Conservation, Urban Runoff Reduction, and Water Quality</td><td rowspan="2">2010</td><td rowspan="2">Kennedy Jenks Consultants</td><td>Residential</td><td>37</td><td>899</td><td>7%</td><td>-</td></tr>
<tr><td>Commercial</td><td>556</td><td>209</td><td colspan="2">3%</td></tr>
<tr><td rowspan="2">MWDOC SmarTimer Rebate Program Evaluation</td><td rowspan="2">2011</td><td rowspan="2">A&N Technical Services, Inc.</td><td>Residential</td><td>49</td><td>70</td><td>9%</td><td>-</td></tr>
<tr><td>Commercial</td><td>727</td><td>132</td><td colspan="2">28%</td></tr>
</table>

[Z] WBIC = Weather-based irrigation controller

[Y] Commercial sites had dedicated irrigation meters

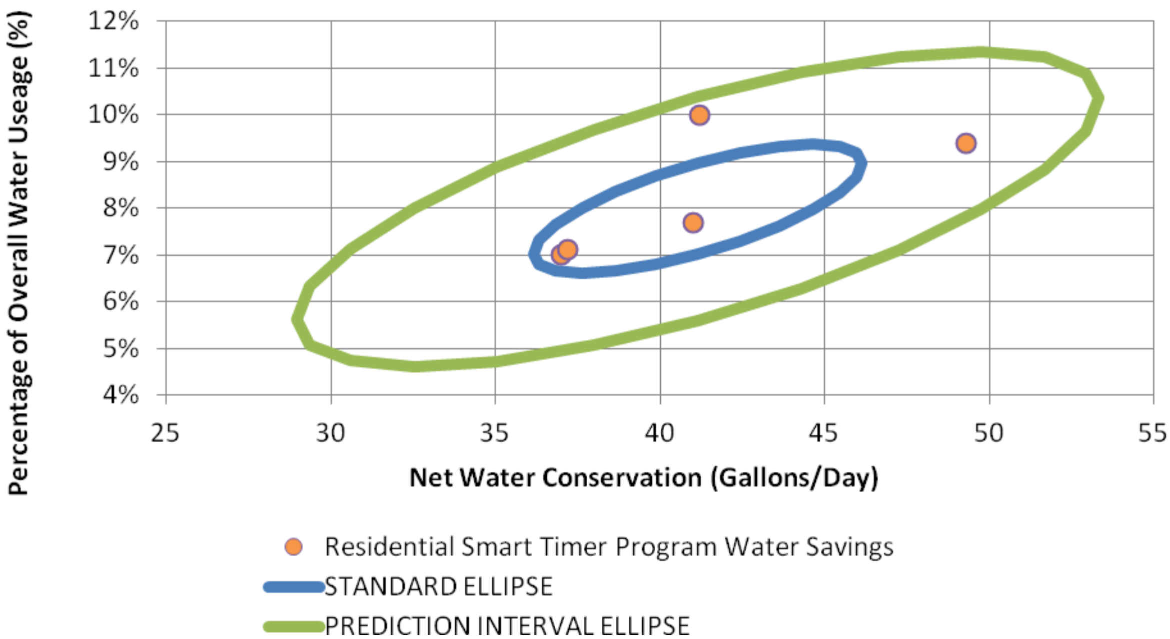

Figure 1. Residential program evaluation water savings with standard and prediction interval ellipses at the 95% confidence level.

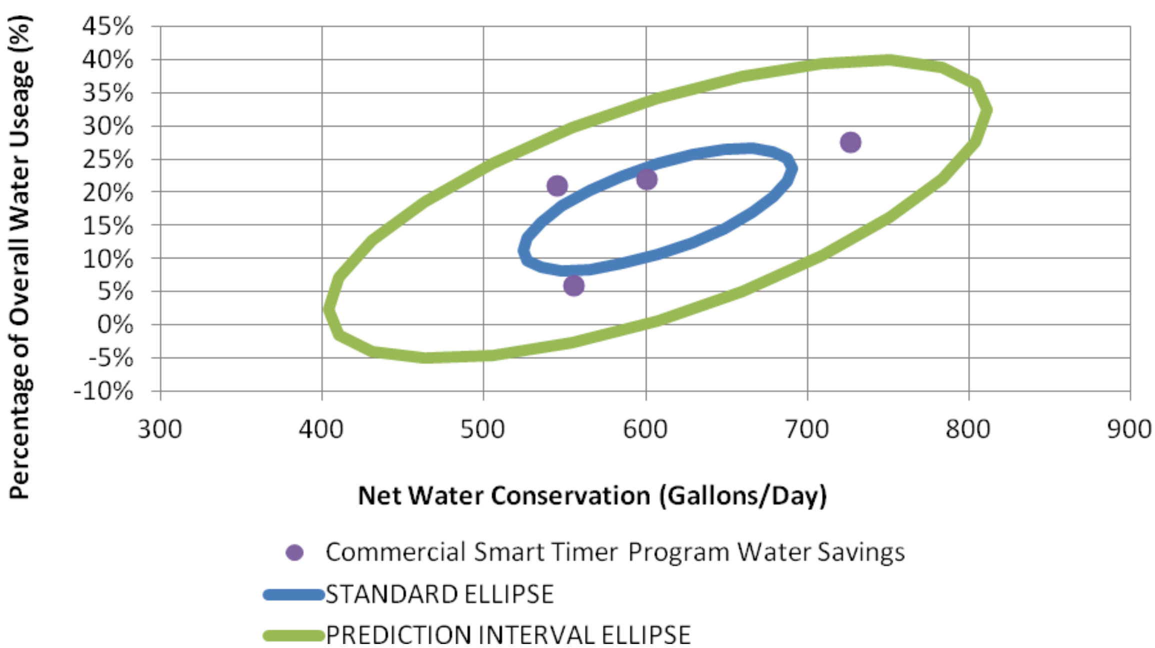

Figure 2. Commercial program evaluation water savings with standard and prediction interval ellipses at the 95% confidence level.

Benchmark of Water Savings Potential

As the actual system efficiency was unknown, the system efficiency was considered at two scenarios to determine the water savings potential: a common industry assumption of 80% and a lower assumption of 55%. Note, this potential for water savings resulting from over-irrigation, that which is excessively applied, is a proxy for management and greater in Scenario 1 (Table 2), particularly in fall and winter months. In Scenario 2, with an equivalent plant-water need to Scenario 1, more water is used to compensate for system inefficiencies and, therefore, there is a lesser amount of water savings potential (Figures 3 and 4).

Using a multiple regression model of the outdoor water use (inches) at the census tract level with air temperature, precipitation, and income showed an R^2 of 0.67 ($p < 0.0001$). The increasing air temperature had the greatest influence on water use patterns, explaining 65% of the increase in use. Additionally, increasing precipitation explained 2.6% of the decrease in total outdoor water use, while income only influenced 0.8% of the trend irrigation water use.

Analysis of over-irrigation using the multiple regression model of outdoor water use at the census tract level resulted in an R^2 of 0.26 ($p < 0.0001$). An increase in air temperature explains 22% of the increase in over-irrigation. In this analysis, increased income explains 3% of the decrease in over-irrigation, which is contrary to other research (Hanke and Mare 1982). Variation in precipitation explains 2% of the trends in over-irrigation. However, precipitation events also correlate with lower air temperature in this region, with a Pearson's correlation coefficient of 0.51 (Greco 2013).

Previous studies have found that ET_O and weather events significantly affect outdoor water use practices (Danielson et al. 1980; Duble 1997; DeOreo et al. 1997; Haley, 2012). A five-year study conducted across 221 communities in Texas found correlation (R^2=0.39) between per capita water use in relation to climate, average water price, and annual income (Griffin and Chang 1989). A more recent two year study conducted in Austin, Texas with 803 participating homes found residential outdoor water use to correlate (R^2=0.204) with temperature, rainfall, ET, household size, appraised value, lot size, and presence of a pool (Tinkler et al. 2005). Similar results were also reported in a study conducted in Malmo, Sweden, where rainfall, household income, household size, age of home, and water prices were modeled (R^2=0.259) (Hanke and Mare 1982).

Table 2. Irrigation applied in excess of that needed to compensate for system inefficiencies, shown by percent of homes and water use that is applying irrigation.

System Efficiency	Percent of Homes Resulting in Over-irrigation				Percent of Total Use Resulting from Over-irrigation			
	Spring[Z]	Summer[Y]	Fall[X]	Winter[W]	Spring	Summer	Fall	Winter
Scenario 1: 80%	29%	35%	44%	36%	9%	8%	10%	14%
Scenario 2: 55%	16%	21%	34%	24%	10%	5%	4%	6%

[Z] Spring: months of March, April, and May
[Y] Summer: months of June, July, and August
[X] Fall: months of September, October, and November
[W] Winter: months of December, January, and February

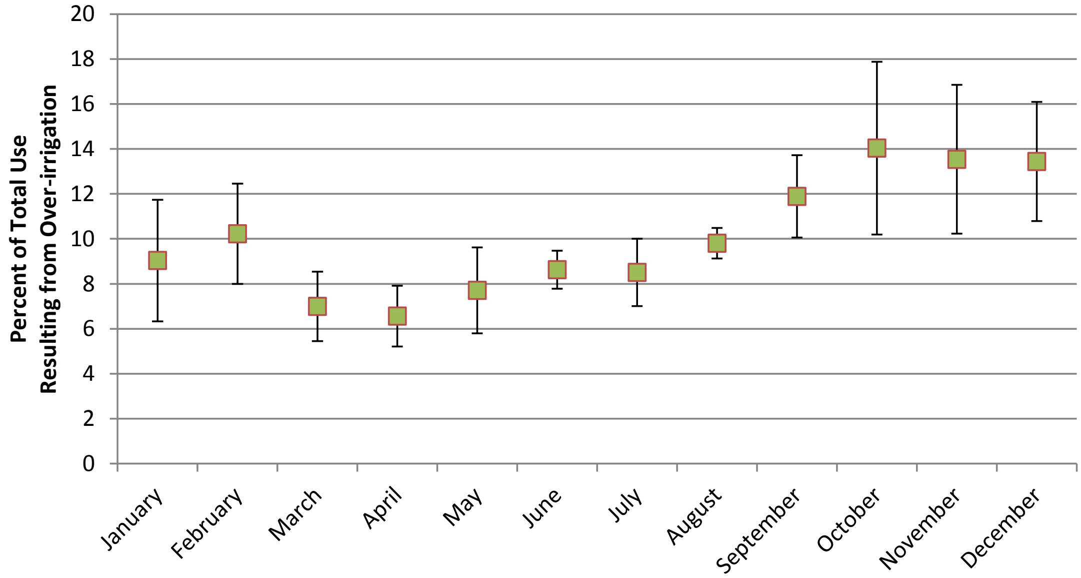

Figure 3. Percent of total single-family residential water use that is over-irrigation at 80% system efficiency.

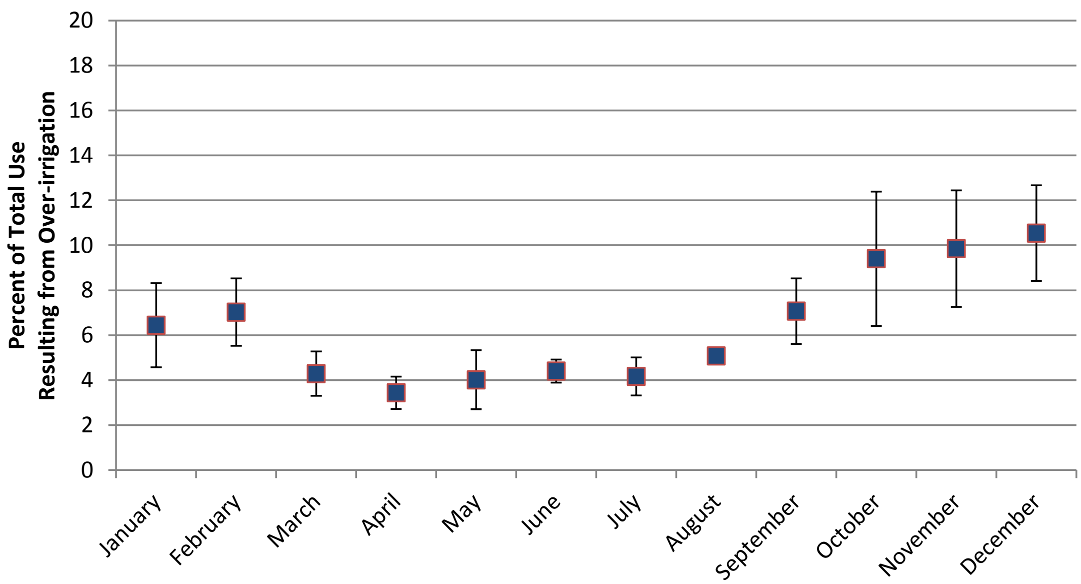

Figure 4. Percent of total single-family residential water use that is over-irrigation at 55% system efficiency.

Conclusions

Meta Analysis of Program Evaluation

The predictive ellipses developed from the evaluations conducted within the MWDOC service area since 2001 allude to a potential total household water savings of approximately 5% to 11% from the inclusion of a weather based irrigation controller. Actual evaluation results ranged from 7% to 10% of total household water savings. These devices can be considered a proxy for better management at the site and more closely aligns with the system efficiency from Scenario 2 in benchmarking the water savings potential.

Benchmark of Water Savings Potential

When, benchmarking the water savings potential within a sample set of more than 34,000 usable accounts of the 50,000, the potential for water savings primarily from management is assumed from Scenario 1 where the system efficiency is 80%. This Scenario suggests between 8% and 14% improvement by reducing over-irrigation resulting from mismanagement.

Further, this analysis suggests that the potential for water savings from management is minimized when the system has greater inefficiencies. The additional water applied is needed to compensate for the system inadequacy, leaving a smaller potential for water savings from scheduling. This analysis suggests that the management potential for savings at the sites where system efficiency is 55% ranges from 4% to 10%.

Air temperature resulted in the strongest predictive variable of irrigation trends. Even though some customers are decreasing irrigation in response to rain, these rain events are infrequent in the local climate. Precipitation events also correlated with lower air temperature, reducing the predictive power of that variable.

Acknowledgements

The Municipal Water District of Orange County would like to thank the following partners in this project: the United States Department of Interior - Bureau of Reclamation, United States Department of Agriculture - Natural Resource Conservation Service, State of California Department of Water Resources, Metropolitan Water District of Southern California, City of Anaheim, City of Brea, City of Buena Park, East Orange County Water District, El Toro Water District, City of Fountain Valley, City of Fullerton, City of Garden Grove, Golden State Water Company, City of Huntington Beach, Irvine Ranch Water District, City of La Habra, City of La Palma, Laguna Beach County Water District, Mesa Water District, Moulton Niguel Water District, City of Newport Beach, City of Orange, City of San Clemente, City of San Juan Capistrano, City of Santa Ana, Santa Margarita Water District, City of Seal Beach, Serrano Water District, South Coast Water District, Trabuco Canyon Water District, City of Tustin, City of Westminster, and the Yorba Linda Water District.

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Fort Collins Sprinkler Audit Program

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Abstract: *Since 1999, Fort Collins Utilities has administered a sprinkler system -audit program as part of its water conservation efforts. The program informs and educates our community about how to run sprinkler systems efficiently. The audit consists of a full evaluation of every zone, a catch can test for a rotor and a spray zone to determine preciptation rates and distribution uniformity, and a recommended irrigation schedule. In a typical season, auditors complete 350-450 homes and 10-15 HOA audits. An analysis of 671 sprinkler audit participants showed an average of 20 percent water savings on outdoor water use. This indicates that customers are continuing their conservation efforts after their sprinkler audit. This and other conservation programs have helped lower the overall water use in Fort Collins by 25 percent in ten years.*

Keywords: sprinkler, audit, water conservation, landscape water, Fort Collins, sprinkler efficiency, sprinkler program

Fort Collins Sprinkler Audit Program

Since 1999, Fort Collins Utilities has administered a sprinkler system audit program as part of its water conservation efforts. The program seeks to inform and educate our community, one household at a time, about how to run sprinkler systems efficiently.

The free audits are offered to single-family homes and homeowner associations (HOAs). An analysis of audit participants' water use found that they saved an average of 20 percent of their outdoor water use.

Sprinkler head with catch cans

An Evolving Program

Fort Collins Utilities Water Conservation Specialist, Laurie D'Audney, with the help of Brent Mecham, formerly from Northern Water, currently Irrigation Association Industry Development Director, created the framework for the program. The first year of the program one auditor performed 60 home audits. Only basic training was provided, large bowls were used as catch cans and handouts were minimal. Believing in continuous improvement, program changes were made, including training, forms, reports, scheduling and handouts. Now during a typical season, up to five auditors complete 350-450 home and 10-15 HOA audits. Over the past 13 years, 3,434 homes and 103 HOAs have received audits.

Home Audits

For a residential audit, auditors meet one-on-one with customers at their home for up to two hours. The resident who operates the sprinkler system typically participates in the audit to learn about their system and see firsthand any maintenance needs. They learn how the lawn uses water, how to program the controller and the importance of periodic system checks. The auditor prepares a report detailing recommendations for scheduling changes, maintenance needs and system upgrades. Information about available sprinkler equipment rebates is also provided.

An auditor will:

- Inspect each zone to identify maintenance needs
- Perform catch can tests to measure the application rate and how evenly water is being applied
- Measure system pressure and root depth
- Develop a custom watering schedule
- Share the results and recommendations with the homeowner

Auditor educating a homeowner

HOA Audits

HOA representatives and the landscape maintenance contractor accompany the auditor for what could take four hours. Each zone is visually evaluated for any leaks, broken or misaligned sprinkler heads and poor coverage. Catch can tests are not performed for these large properties as the time is better spent identifying maintenance issues. The audit report includes a zone-by-zone evaluation, photos, explanation of problems, watering schedule and a prioritized list of recommended maintenance tasks. Because recommendations for large properties may be expensive, the report is typically presented at an HOA board meeting so the suggestions can be explained and questions answered.

Staffing and Training

Utilities staff recruit, hire and supervise four or five seasonal auditors who work from mid-May to mid-September. Many are college students as the summer schedule works well for them; some return multiple summers. Auditing experience isn't necessary but good communication skills are mandatory. In addition, a program administrator is hired to provide scheduling, keep supplies available and send the audit report and an evaluation to participants.

Auditor training

A comprehensive three-day training includes the basics of sprinkler systems, hands-on practice with controllers and role-playing audits. Colorado State University professors provide training about soils, turf grass and water use. An important part of the training is how to communicate with customers in a way to effectively educate our diverse population. During the first week of audits, new auditors team up in the field with seasoned auditors. First, the experienced auditor models an effective audit. Then it's the new auditor's turn to conduct the audit with coaching from the experienced auditor.

Throughout the summer, staff and the auditors meet bi-weekly to discuss issues and questions that arise, share stories from the field and receive more advanced training.

Scheduling

Appointments for home audits are scheduled Monday through Friday for two hours at 8:30 a.m., 10:30 a.m., 1 p.m. and 3 p.m. Late day or Saturday appointments are also accommodated. Auditors work alone and perform four audits a day with a half-hour lunch. HOA audits are scheduled with two auditors for four hours.

Customers request an audit online or by voice mail. An online scheduling program is used to track customer information, appointments for each auditor and completed audits. Participants receive automated appointment confirmation and reminder emails. One challenge is connecting with people to make an appointment. To help with this, the program's self-scheduling feature will be used in the future. After audits are scheduled, they may be moved between auditors to keep appointments as close together as possible.

Customer Feedback

An online evaluation or a paper copy is sent to participants. In 2013, 84 percent of participants said the audit exceeded their expectations. This percentage has significantly increased over the last few years as we've dedicated more time to training and have an irrigation professional on staff who provides in-depth expertise and support to the auditors. When asked if they had made changes since the audit, 93 percent responded that they had. The most common changes were adjusting sprinkler heads, changing the watering schedule and fixing leaks. All comments are considered and guide future program improvements.

Water Use Tracking

Utilities uses a software tool to track program and rebate participation, and resulting water savings. The software uses customer account records, geographic information system (GIS) data, tax assessor information and current/historic weather data. An analysis of 671 sprinkler audit participants showed an average annual water savings of 12,110 gallons and a median water savings of 7,690 gallons, about 20 percent of their outdoor use. This data indicates that customers are continuing their conservation efforts after their sprinkler audit.

Budget

The program budget is allocated through the City's biennial budget cycle. Annual costs run $17,000-$18,000 per year, including equipment, training, publicity, mileage and labor. The cost per audit typically ranges between $40 and $50.

Annual Planning Schedule

February: begin auditor recruitment
April: complete hiring
April-May: finalize training schedule, materials and equipment
End of May: three-day training
June-August: perform audits, ongoing scheduling
September: compile evaluations and write report

Conclusion

Fort Collins is a community of over 151,000 residents located just east of the Rocky Mountains. Fort Collins Utilities provides water, wastewater, stormwater and electric services to the community. Since 1999, the City has offered a free sprinkler system audit program as part of its water conservation efforts. The constantly evolving program receives high accolades from those who have received audits for what they learned during the audit and the professionalism of the auditors. Water use analysis has shown that residents continue to save an average of 20 percent of their outdoor water use long after their audit is performed. The program is gaining attention from neighboring water districts that have contracted with the City to audit their customers.

Effectiveness of In-Line Drip Tubing on Turf Quality Based on Depth and Manufacturer

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Purpose

This paper discusses the methodology and results to date of 16 months of an initial 2 year drip line irrigation study commenced on February 14, 2012 in central Florida outside of the Orlando area on turf grass (St. Augustine 'Floratam'). The purpose of this study was/is to compare the turf show quality, health and vigor of three different subsurface drip burial depths utilizing three different manufacturer's products. Burial depths were surface, 2 inches and 4 inches. Manufacturers drip lines tested were Netafim Techline, Toro Drip In PC Brown and Rain Bird XF Drip line.

Methodology

The test area consists of four 15 x 15 foot plots irrigated in 5 foot x 15 foot sections, one for each manufacturer (Figure 1). The four plots are individually controlled with their own Irritrol 700-01valve from a Rain ESP-LX controller communicating with a central control system. A rain shut off for the controller is within 300 feet. Each plot also includes a 200 mesh wye strainer and a 30 psi in line pressure regulator. The drip line is installed on 12 inch row spacing with a 12 inch emitter spacing. Each emitter is 0.9/1.0 gph depending on the manufacturer. ET calculations are provided by a Campbell Scientific weather station located approximately 30 feet from the plots installed on the same type turf grass.

The test plots consist of 2 plots (#1 and #2) with the drip installed at the surface, one with a 2 inch burial depth (#3) and the last (#4) with a 4 inch burial depth. The difference between plots #1 and #2 is in how the drip line is laid out. In plot #2 the drip line is installed 90 degrees opposite of plot #1 and the order of manufacturers is different to see if either will influence the results. The four plots are evaluated for turf quality each month based on the University of Florida protocol. Weather is tracked daily and reported monthly.

The plots are scheduled to irrigate four days per week with a landscape coefficient of 0.75 (L_T=0.75, L_D=1.0, L_{MC}=1.0) based on the Irrigation Associations Landscape Auditor references. Precipitation rate for each plot is programmed at 1.48 inches per hour. The water supply is tertiary treated reclaimed.

Initially, the St. Augustine turf was grown in for two weeks from sod with a single rotary sprinkler for each plot to supplement the drip line. Following the first two weeks, the drip lines were operated 30 minutes per day.

Data Recording and Reporting:

Beginning in June 2012, photos of each plot are taken monthly with a brief description of the observed quality of the turf. The turf quality rating for each plot is recorded each month as show in Table 1. The ratings range from 1 to 8 based on appearance (see attached).

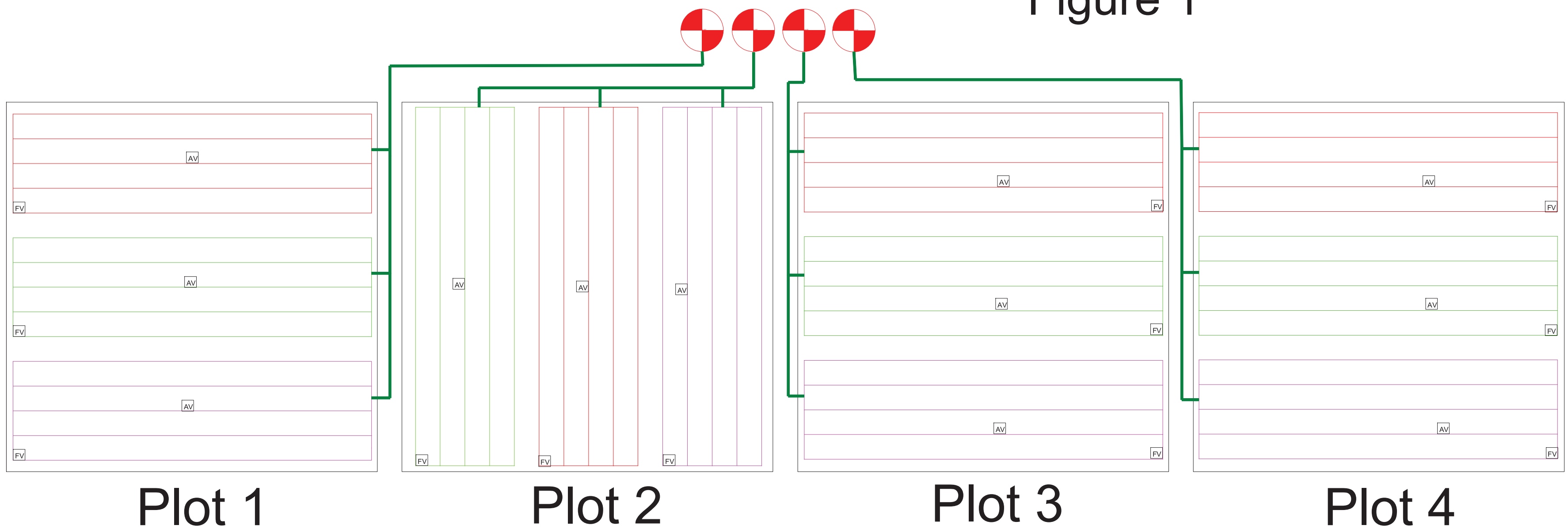
Table 1: Example Turf Quality Ratings

Plot #	Rating			Average bury rating
	Netafim	Toro	Rain Bird	
8-12 0" bury	7	7	7	7.00
8-13 0" bury	7	7	7	7.00
8-14 2" bury	6	6	6	6.00
8-15 4" bury	6	6	6	6.00
Average product rating	6.50	6.50	6.50	

Conclusions

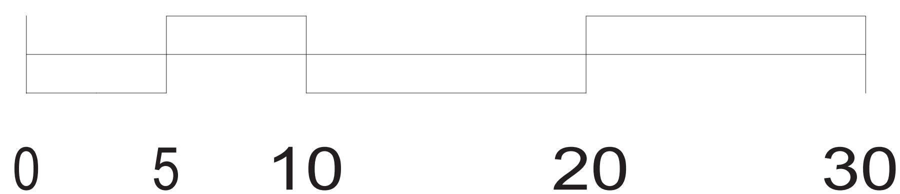
Figure 2 shows the average turf quality trends over the length of the study to date for each plot. To date the study does not reflect any significant differences in either the product of the burial depth due to the amount of rainfall that has occurred during the test period to date.

Figure 1



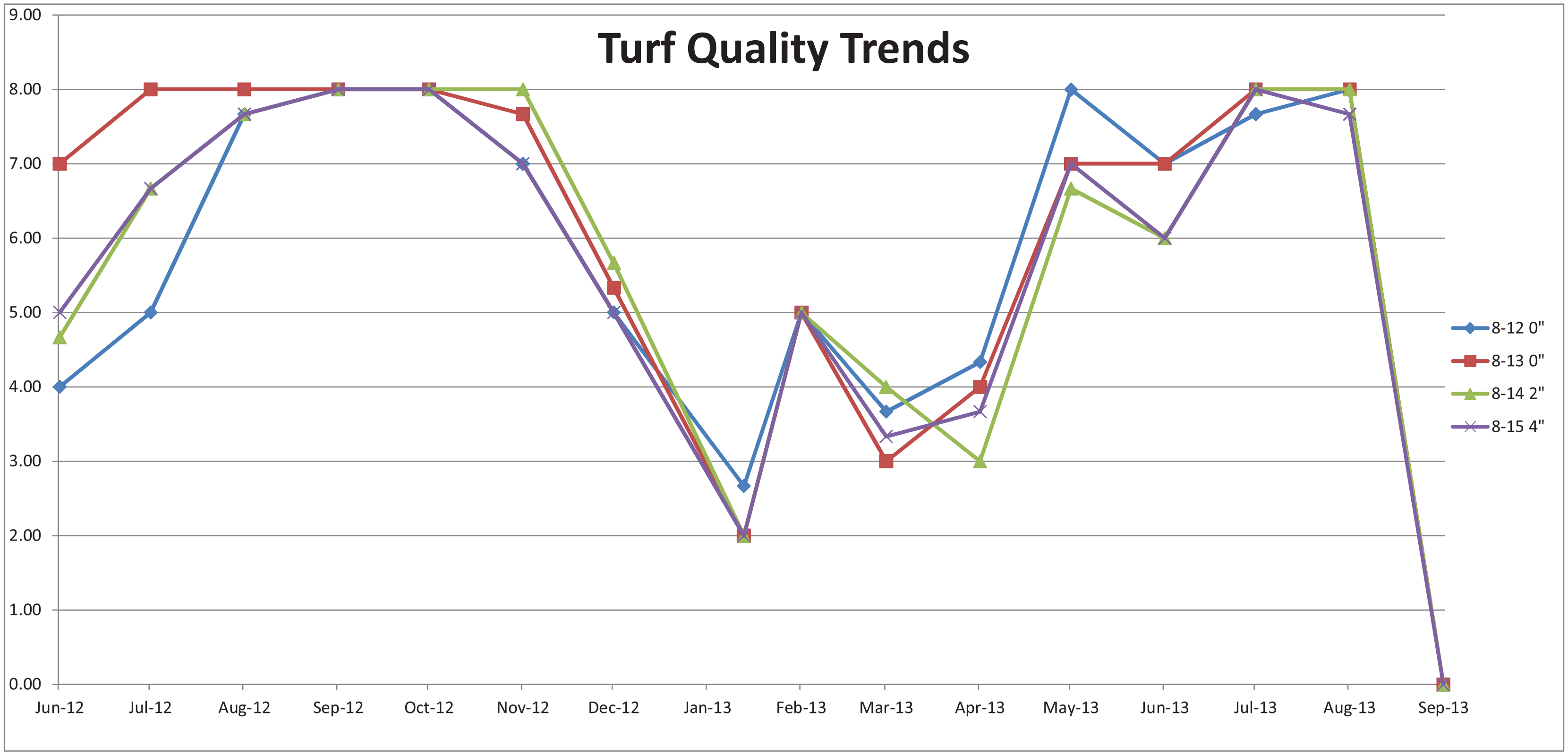
All electric valves to have 200 mesh filtration and 30 psi regulator (low flow).
All piping between valve assembly and drip line manifolds to be 1/2" PVC
Red lines indicate Netafim Techline 12", .92gph
Green lines indicate Toro PC Brown Dripline 12", 1.0gph
Magenta lines indicate Rain Bird XF Dripline 12", .9gph
Each subassembly to have a air/vacuum valve and flush valve installed in a 6" round box in locations shown.

Plot 1 - Surface installed drip line
Plot 2 - Surface installed drip line
Plot 3 - Installed 2" below grade
Plot 4 - Installed 4" below grade



1" = 10'

Figure 2


Turf Quality Trends
9.00
8.00
7.00
6.00
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0.00
Jun-12
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Aug-12
Sep-12
Oct-12
Nov-12
Dec-12
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Mar-13
Apr-13
May-13
Jun-13
Jul-13
Aug-13
Sep-13
8-12 0"
8-13 0"
8-14 2"
8-15 4"

Turfgrass Quality Reference Guide
GCREC ET Controller Study

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Reduced Scheduling Multiplier for High Irrigation Distribution Uniformities

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Abstract. *The Irrigation Association has advanced the use of a SM (scheduling multiplier) to adjust landscape watering schedules based on the DU_{LQ} (distribution uniformity - low quarter) obtained from sprinkler audits using surface catchments. However the SM algorithm appears to be overly generous as DU_{LQ} increases.*

Present calculation: $SM = 1 / (0.4+0.6*DU_{LQ})$

Proposed calculation: $SM = 1/(0.352 + 0.72 * DU_{LQ})$

The proposed change would have minimal effect on calculation of the SM when DU_{LQ} is 0.40, but would increasingly lower the calculated SM until SM reaches a minimum value of 1.0 when DU_{LQ} is 0.90 or greater.

Keywords. Distribution uniformity, sprinkler audit, catch can test, scheduling multiplier, irrigation application efficiency.

Background and Methodology

Northern Water has hosted the Irrigation Association's Certified Landscape Irrigation Auditor class in January 2011, 2012, and 2013. A temporary sprinkler system was setup for these classes inside one end of a heated 20-stall vehicle garage. This system has six sprinklers on 15-ft square spacing, arranged to cover a 15-ft by 30-ft area.

The sprinkler system was constructed to allow placement of standard catchment devices on a grid spacing of 3.75-ft, for a total of 32 catchment locations. Up to three catchments can be positioned at each location, with care taken to insure the top of each device is at equal height with the others. Catchment height is established relative to a virtual ground surface at the top of the sprinkler bodies, so as to mimic catchment installation in the field.

During sprinkler tests, operating pressure is maintained at manufacturer specified levels. A flow meter provides gross irrigation application. This paper includes results from sprinkler catchment tests conducted by Northern Water staff (not class participants) to insure consistency of methods, procedures, and technique.

Indoor use of the temporary sprinkler system affords year-to-year standardization of the sprinkler system and catchment locations, along with elimination of wind effects. Every effort has been made to keep changes in sprinkler nozzles as the only variable of significance. Measurements at each station can thus be compared to corresponding measurements made at that same catchment station with a degree of confidence.

Measurements Uncertainty for Catchment Depth

In 2011 a sprinkler audit was performed with three types of catchments at each station. The test was replicated the following day with addition of a fourth type of catchment. Table 1 summarizes the measurements as standardized to volume in milliliters for the collection area of the CalPoly style catchment . The variability of measurements at each station reveals the uncertainty inherent in such measurements.

Table 1. Comparison of Measurements to CalPoly Style Catchment - January 20, 2011.

	CalPoly	Cereal Bowl	Reclamation	Rain Gauge
Number of catchments	32	32	32	32
Ave catch volume (ml)	22.72	22.72	22.72	22.90
Ave LQ catch (ml)	16.63	17.13	17.47	19.43
DU_{LQ}	0.73	0.75	0.77	0.85
Value just greater than highest of low quarter	20	21.87	19.96	21.63
R^2 from linear regression		0.65	0.82	0.36
Standard error from linear regression (ml)		2.63	1.88	3.58

During 2011 and 2012, four sprinkler audits were replicated (or triplicated) the same day, in an effort to determine repeatability of the audits. Measurements were again standardized to volume in milliliters for the collection area of the CalPoly style catchment . These tests are summarized in Table 2 and Table 3. Although the summary results would generally be considered quite close, the variability of individual measurements at each station yet reveals noise or uncertainty in these measurements.

SM calculated from DU_{LQ} indirectly adjusts for some spray, drift, and evaporation losses. DU_{LQ} is derived from net irrigation catchment rather than the gross irrigation applied. Hence some adjustment for application losses is already built-in.

Table 2. Comparison of Measurements from Replicated Audits - January 2011-2012.

	January 21, 2011		January 25, 2012	
	Rain Gauge 1	Rain Gauge 2	CalPoly A1	CalPoly A2
Number of catchments	32	32	32	32
Ave catch volume (ml)	74.95	76.72	22.34	22.91
Ave LQ catch (ml)	40.56	43.60	17.00	17.63
DU_{LQ}	0.54	0.57	0.76	0.77
Value just greater than highest of low quarter	48.67	54.08	20	21
R^2 from linear regression		0.95		0.94
Standard error from linear regression (ml)		6.18		1.09

Table 3. Comparison of Measurements from Replicated Audits - January 26, 2012.

	January 26, 2012		January 26, 2012		
	CalPoly B1	CalPoly B2	CalPoly C1	CalPoly C2	CalPoly C3
Number of catchments	32	32	32	32	32
Ave catch volume (ml)	43.09	42.38	31.56	32.38	31.84
Ave LQ catch (ml)	21.50	22.75	22.38	22.88	22.25
DU_{LQ}	0.50	0.54	0.71	0.71	0.70
Value just greater than highest of low quarter	30	33	27	28	27
R^2 from linear regression		0.95		0.94	0.93
Standard error from linear regression (ml)		3.86		2.05	2.18

In order to reduce the apparent noise in measurements at each catchment station, a multiple linear regression was accomplished for 17 catchment audits. The regressions provided calculated measurements at each station based on x-y spatial position. It was then possible to expand the 32 actual catchment stations to 800 virtual stations. Through the regression, measurement noise was reduced in the calculated values for catchment depth and high/low trends across areas were more readily identified. The

DU_{LQ} computed from these calculated measurement depths trended significantly higher with increasing DU_{LQ} than the original calculated DU_{LQ}.

The form of the multiple linear regression equation was:

$$Catch\ (ml) = C0 + C1*x + C2*y + C3*x*y + C4*x^2*y + C5*x*y^2 + C6*x^2 + C7*y^2$$

Results

Table 4 summarizes the results from the multiple linear regressions. Not all DU_{LQ} increased. In three cases, spatial trending of lower depth measurements captured by the multiple linear regression resulted in lower calculated DU_{LQ}.

Table 4. Comparison of DU_{LQ} and SM for 32 Actual vs. 800 Calculated Catchment Measurements.

	DU_{LQ} from 32 catchments	DU_{LQ} from 800 calculated catchments	DU_{LQ} change	SM for DU_{LQ} from 32 catchments	SM for DU_{LQ} from 80 calculated catchments
1	0.73	0.77	0.04	1.19	1.16
2	0.85	0.90	0.05	1.10	1.06
3	0.78	0.94	0.16	1.15	1.04
4	0.54	0.58	0.04	1.38	1.33
5	0.57	0.62	0.05	1.35	1.30
6	0.59	0.61	0.03	1.33	1.30
7	0.82	0.89	0.07	1.12	1.07
8	0.76	0.91	0.14	1.17	1.06
9	0.77	0.90	0.13	1.16	1.07
10	0.50	0.34	-0.16	1.43	1.65
11	0.54	0.49	-0.05	1.38	1.44
12	0.71	0.85	0.14	1.21	1.10
13	0.71	0.87	0.16	1.21	1.09
14	0.70	0.82	0.12	1.22	1.12
15	0.78	0.81	0.03	1.15	1.13
16	0.66	0.71	0.05	1.26	1.21
17	0.52	0.49	-0.03	1.40	1.44
Ave	0.68	0.74	0.06	1.25	1.21

Horizontal Movement of Soil Moisture

Assuming homogenous soils, uniform initial moisture content, and no hysteretic moisture content-pressure head relation, Elmaloglou, S., and Diamantopoulos, E., 2006 developed methodology for predicting the surface and vertical components of the wetting front under a point source emitter. They utilized the relations developed by van Genuchten, M.Th., 1980. Their results calculated a wetted radius of nearly 13.5 inches for a sandy loam soil and just over 16 inches for a silt loam, using class average values for two of the 12 USDA soil classes. This further corroborates the much relied upon phenomena of horizontal movement of water after it infiltrates the soil.

Consequently it is commonly assumed that soil moisture DU_{LQ} is higher than the DU_{LQ} calculated from surface catchments. However, DU_{LQ} may actually decrease in the presence of significant soil cracking, surface sealing, or similar conditions.

Irrigation Management to Improve Soil Moisture Distribution Uniformity

Elmaloglou, S., and Diamantopoulos, E., 2010 concluded for the same irrigation depth, same dripper spacing, and same soil that the vertical component of the wetted zone is deeper for a smaller/slower discharge rate than for a higher/faster one. Hence wetted radius would decrease and risk of deep percolation loss increase.

Application rates for sprinkler irrigation typically exceed steady state soil infiltration rates. The management practice of cycle and soak would help to maintain a higher/faster net application rate under sprinklers without causing surface runoff losses. This effectively increases horizontal soil moisture movement and increases soil moisture DU_{LQ}.

A second management practice to increase horizontal movement of soil moisture and thus increase soil moisture DU_{LQ} is to irrigate deeply and infrequently. Light, shallow irrigations simply do not provide the same opportunity for homogenizing soil moisture in the root zone.

Conclusions

The inherent variability of sprinkler catchment measurements creates random noise that artificially lowers higher DU_{LQ} and results in larger SM than necessary. Horizontal movement of soil water from wetter zones to dryer zones will further improve the soil moisture DU_{LQ} in the active root zone, particularly when surface catchment DU_{LQ} is higher. Additionally, several common irrigation management factors can further improve soil moisture DU_{LQ} over surface catchment DU_{LQ}.

Present calculation: $SM = 1 / (0.4+0.6*DU_{LQ})$

Proposed calculation: $SM = 1/(0.352 + 0.72 * DU_{LQ})$

The proposed change would not affect calculation of SM when DU_{LQ} is 0.40, and use of SM is not recommended for DU_{LQ} lower than 0.4. The new calculation of SM will have SM descend to 1.0 when DU_{LQ} is 0.90 or greater.

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Quantifying pressure effects on flow rate and water application uniformity of microirrigation emitters

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Abstract. *Microirrigation can be an effective method of delivering water to plants from elevated tanks but the head incident to drip emitters may be significantly below that recommended by the emitter manufacturer to provide the specified flow rate (q). The objective of this study was to quantify the effect of variable pressure on q and water application uniformity (WAU) of selected drip emitters. Flow rate was measured at three different heads (3.5 ft., 5.5 ft., and 57.7 ft.) and WAU was calculated as 1 – cv where cv equaled the standard deviation divided by the mean q from eight replicates of each emitter. Mean q ranged from zero to 102% of manufacturer specified q (MSFR) at 5.5 ft. of head and from 95 to 193% of MSFR at 57.7 ft. WAU was greater than 0.90 for more than half the emitters at 5.5 ft. and for 75% of the emitters at 57.7 ft.*

Keywords. microirrigation, point source emitters, low pressure, flow rate, water application uniformity

Introduction

Microirrigation represents an ideal, efficient way of distributing water to plants from elevated vessels such as rainwater catchment barrels or tanks carried in truck beds or trailers. Choosing suitable drip components that function adequately under the low heads provided by the water level in these vessels (commonly less than 10 ft.), however, is problematic since the flow rate (q) specified by the manufacturers of drip emitters has been measured under much higher heads (typically greater than 20 ft. or 8 psi). While it's logical to assume that q will decrease with decreased pressure (Burt and Styles, 1999; Li, et. al., 2009; Smajstria et. al., 1997) it might also be assumed that water application uniformity (WAU), and hence overall efficiency, of a microirrigation system will decrease when operated at a pressure lower than that specified for the emitters. As in any irrigation system, this would certainly be true if available pressure is insufficient to overcome friction loss caused by excessive lateral lengths and/or total system q or elevation changes, it may not be true in systems used to irrigate small gardens or landscapes on fairly level ground at low total q.

While reports of studies that measure the effect of ultra-low pressure on q and WAU of point source emitters are difficult to find, a few papers reporting measurements from line source systems have been published. In measurements taken from a low-cost line source system in Nepal (Polak, et. al. 1997), for example, *q* variations ranged from 12 to 23% (equivalent to 0.88 and 0.77 WAU) between 25, 0.027 in. diameter holes spaced 30 in. apart in four, 0.54 in. ID laterals at three heads. Average emitter *q* at heads of 6.6 and 9.8 ft. were 59.4 and 80.2%, respectively, of that at 13.1 ft. In a laboratory test of a manufactured drip kit for use by smallholder farmers in Zimbabwe, Chigerwe et al. (2003) reported kit water application uniformities of about 91% (0.91) at heads ranging from 1.6 ft. to 9.8 ft. Li, et al. (2009) compared measured *q* of three different labyrinth flow path emitters to modeled *q* under micro-pressures and observed suitable turbulent flow at pressures as low as 1.5 psi.

This study was implemented to evaluate the effects of substandard pressure on the *q* and WAU of several commercially available point source drip emitters so that objective recommendations on emitter selection could be provided to irrigators using rainwater catchment systems or other low head systems.

Materials and Methods

Flow rate measurements were taken from twenty different models of point source emitters at two substandard heads (3.5 ft. and 5.5 ft.) in September 2011 at New Mexico State University's Agricultural Science Center at Farmington. These two heads were chosen to simulate potential conditions of rainwater catchment systems and tanks in a pick-up truck bed, respectively. Measurements at these two heads might also provide an indication of *q* change as water level decreases in an elevated drum during irrigation. Water was provided at constant head to drip laterals by an elevated 55-gallon water tank. Water was fed to the tank by a hose attached to a pressurized irrigation pipe and water level in the tank was held constant with a float valve. Outflow from the tank was controlled with a ¾ inch ball valve and filtration was provided by a ¾ inch (150 mesh equivalent) disk filter. Five different emitter models were installed at 24-in. intervals into four separate, 0.6 inch ID, 80 foot long PE laterals in eight, 10-foot long reps: 0-10 feet, 10-20 feet, 20-30 feet, etc. Emitter order was randomized in each rep. A ¾ inch PE line delivered water (through a reducer) to each lateral which was hung level on a wire mesh fence at a height of about 6 inches above ground to facilitate emitter *q* measurements.

In 2012, *q* was measured from the same emitters as in the 2011 evaluation. Lateral and emitter arrangement were identical but incident pressure at the header was maintained at 25 psi by a pressure reducer installed between a high pressure (>50 psi) hose and the lateral.

In all evaluations, after pressurizing the laterals, a glass beaker was used to catch water from emitters for a timed period (1 to 4 minutes) and then the collected water was poured into a graduated cylinder for volumetric quantification in milliliters (ml). Equation 1 was used to convert *q* from ml/second to gallons per hour (gph) for comparison to the manufacturers specified flow rate (MSFR).

$$q = ml / sec \times 3600 / 3785 \quad \text{[Eq. 1]}$$

Where:

q = flow rate in gallons per hour (gph)
ml = millimeters of water caught in catch cup
sec = seconds cup was held under emitter
3600 = seconds in 1 hour
3785 = ml per gallon

I all evaluations, Equation 2 was used to calculate WAU.

$$WAU = 1 - cv \quad \text{[Eq. 2]}$$

Where:

WAU = water application uniformity (decimal; 1.0 indicates perfect uniformity)
cv = standard deviation / mean of all *q* measurements from given emitter model

Seventeen of the twenty drip emitters used in the evaluations were purchased from 'The Drip Store' (http://www.dripirrigation.com/) and the model number shown actually represents their part number. Three emitters were purchased from a local home improvement retailer. Emitter styles were variable (e.g. button, flag, Katif, etc.) and manufacturer specified flow rates (MSFR) ranged from 0.5 to 4.0 gph (Table 1). Most of the emitters utilized a labyrinth path design to create a turbulent flow and silicon diaphragm for self-flushing. The exceptions were the flag emitters which used a screw-like or spiral flow path and a take-apart feature for manual cleaning. The D015 emitter could also be taken apart for cleaning. Manufacturer's specified operating pressures (MSOP) ranged from 7 psi (16 ft. of head) to 50 psi (115 ft. of head). Twelve of the emitters were pressure compensating (PC) and 8 were not (NC).

Statistical Regression Analyses

Since replicates were at varying distances (D) away from the water source along each lateral, emitter *q* was plotted against D and then regression analysis (CoStat 6, 2001) was used to define suspected significant linear or quadratic relationships between *q* and D for each emitter.

Table 1. Drip emitters included in the flow rate and WAU evaluations with manufacturer specified flow rates (MSFR) and recommended operating pressure ranges (MSOP).

Brand Name	Part Number	Type[a]	MSFR gph	MSOP[b] psi
Supertif	D001	button, PC	1.0	8 - 50
Supertif	D002	button, PC	2.0	8 - 50
Supertif	D004	button, PC	3.3	8 - 50
Supertif	D006	side outlet, PC	1.0	8 - 50
unknown	D012	button, NC	1.0	10 - 20
unknown	D013	button, NC	2.0	10 - 20
John Deere	D015	easy-open, NC	1.0	15 - 20
unknown	D021	flag, NC	1.0	10 - 25
unknown	D022	flag, NC	2.0	10 - 25
Katif	D043	low profile, PC	3.3	10 - 50
Katif	D044	low profile, PC	2.0	10 - 50
Katif	D045	low profile, PC	1.0	10 - 50
DIG	D076	button, PC	1.0	8 - 40
DIG	D077	button, PC	2.0	8 - 50
DIG	D078	button, PC	4.0	8 - 50
Netafim	D079	heavy duty, PC	0.5	7 - 45
Netafim	D080	heavy duty, PC	1.0	7 - 45
Orbit 1G	unknown	flag, NC	1.0	unknown
Orbit 2G	unknown	flag, NC	2.0	unknown
Orbit 4G	unknown	flag, NC	4.0	unknown

[a] PC - pressure compensating; NC - non-pressure compensating
[b] Recommended pressure range may be narrower but within operating range

Results and Discussion

Measured average *q* at 5.5 ft. of head ranged from 0.075 gph (emitter D021) to 2.15 gph (emitter D078). These rates were 7.5 and 53.8% of MSFR, respectively (Table 2). The average *q* of all emitters at 5.5 ft. of head was 33.6% of MSFR but the measured *q* from one emitter (D045) was about equal (101.8%) to the MSFR at MSOP (Table 2). The average *q* of all emitters at 3.5 ft. of head, at 14.8 % of MSFR, was considerably less than that at 5.5 ft. As with 5.5 ft. of head, the lowest and highest *q* (0.018 and 0.822 gph, respectively) was measured from emitter models D021 and D078 (Table 2). Water application uniformity (WAU) is a more important consideration than *q* in efficient drip irrigation design unless emitter *q* is so low that it would be difficult to satisfy the plant's daily water requirement during peak ET (e. g. emitter D021). Calculated WAU at a head of 5.5 ft. ranged from a high of 0.957 for the Orbit 4G emitter (a high flow, NC, flag emitter) to a low of 0.376 for emitter D077 (a 2 gph, button style, PC emitter). At 3.5 ft. of head, emitter D013 (button style, NC) exhibited the highest WAU of 0.925 while emitter Orbit 1G (low flow, flag) had the lowest WAU of 0.327 (Table 2). Eleven of the twenty emitters exhibited WAU greater than 0.90 at 5.5 ft. of head but only two of the eleven (D043 and D013) maintained a WAU greater than 0.90 at the lower head (3.5 ft.).

Table 2. Average measured flow rate (*q*)[a], as gph and as % of manufacturer's specified *q* (MSFR), and water application uniformity (WAU) for 20 different point source emitters at two substandard heads (5.5 feet and 3.5 feet). 2011.

Emitter[b] (part number)	5.5 Feet of Head			3.5 Feet of Head		
	Q (gph)	% MSFR	WAU	Q (gph)	% MSFR	WAU
Orbit 4G	0.791	19.8	0.957	0.310	7.7	0.794
D043	0.475	14.4	0.956	0.378	11.5	0.923
D015	0.210	21.0	0.954	0.092	9.2	0.845
D006	0.442	44.2	0.948	0.235	23.5	0.773
D001	0.447	44.7	0.946	0.200	20.0	0.842
D012	0.172	17.2	0.941	0.123	12.3	0.880
D013	0.354	17.7	0.936	0.251	12.6	0.925
Orbit 2G	0.435	21.7	0.933	0.141	7.1	0.797
D044	1.124	56.2	0.928	0.320	16.0	0.603
D002	0.890	44.5	0.928	0.342	17.1	0.717
D004	0.760	23.0	0.925	0.311	9.4	0.714
D076	0.377	37.7	0.897	0.152	15.2	0.526
D021	0.075	7.5	0.893	0.018	1.8	0.596
D045	1.018	101.8	0.855	0.382	38.2	0.575
D078	2.152	53.8	0.828	0.822	20.6	0.688
D022	0.222	11.1	0.825	0.064	3.2	0.681
Orbit 1G	0.305	30.5	0.774	0.123	12.3	0.327
D077	0.775	38.8	0.376	0.560	28.0	0.347
D079	Insufficient data – some units had zero flow					
D080	Insufficient data – some units had zero flow					

[a] Flow rate (q) values represent the mean of eight replications.
[b] Ordered from highest to lowest WAU at 5.5 ft. of head.

Regression Analyses

Although WAU was greater than 0.94 at 5.5 ft. of head for emitters D001 and D012, there was a slightly significant linear decrease in *q* with increasing distance from the water source for these emitters at this head (Figure 1). Conversely, *q* of emitters D002 and D045, increased linearly with increased D (Figure 2) but calculated WAU was marginal for emitter D002 at 0.928 and poor but acceptable for D045 at 0.855.

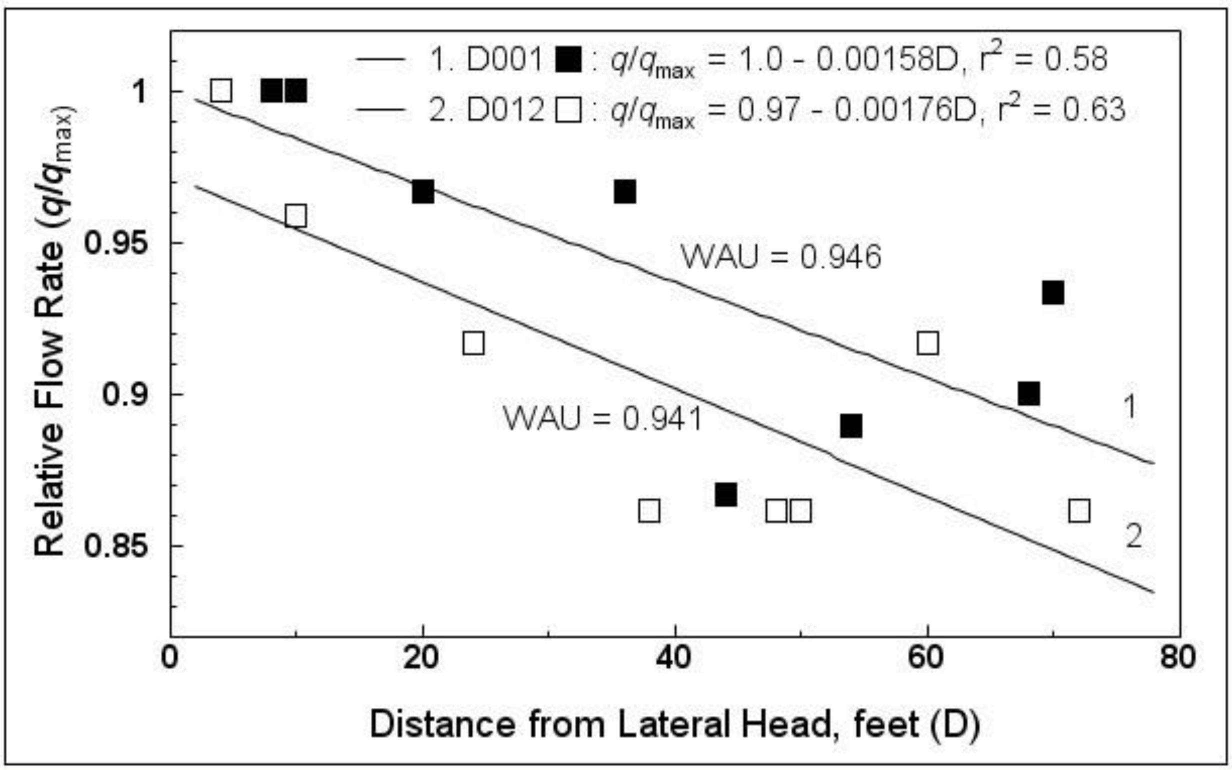

Figure 1. **Relative emitter flow rate (q/q_{max}) with distance (D) of emitter from the head of a lateral for two emitters that exhibited a slightly significant linear decrease in *q* with increased D.**

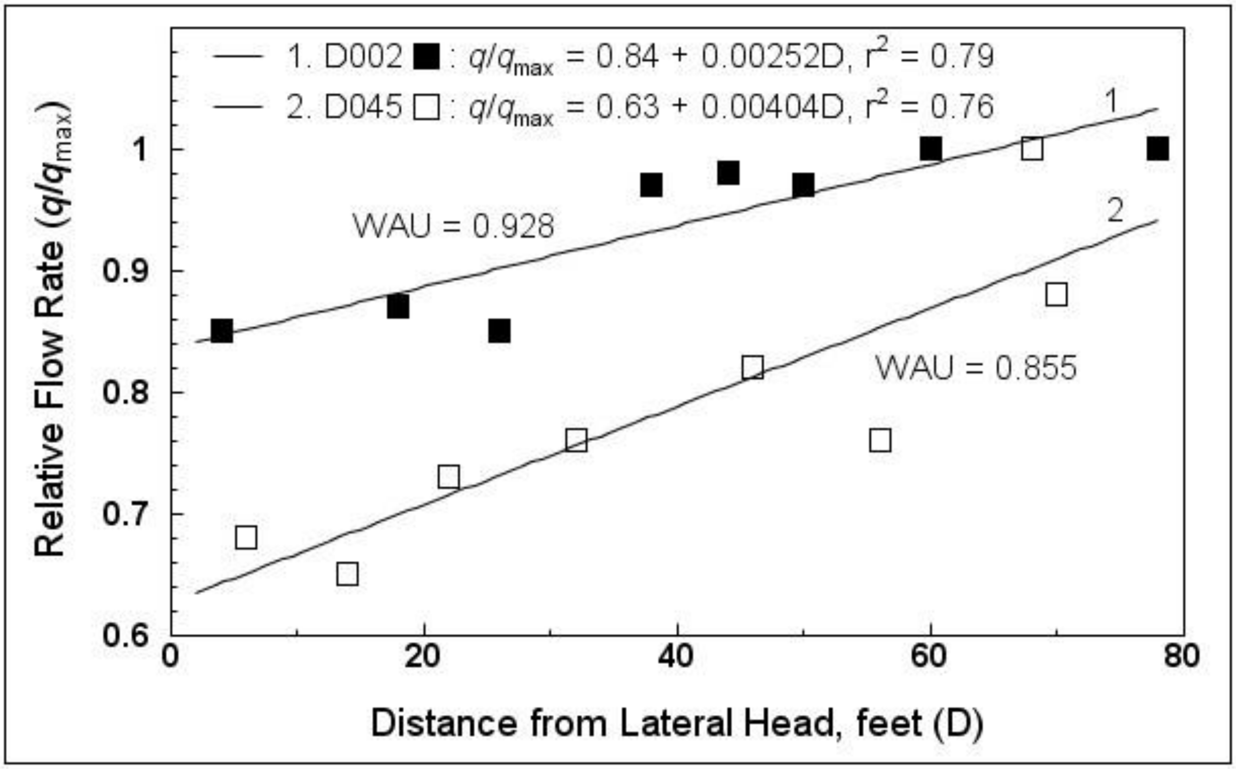

Figure 1. **Relative emitter flow rate (q/qmax) with distance (D) of emitter from the head of a lateral for two emitters that exhibited a significant linear increase in q with increased D.**

At 3.5 ft. of head, a statistically significant curvilinear relationship between *q* and D was found in seven of the twenty emitters where lower *q* towards the center of each lateral (i.e. D between 30 and 60 ft.) than at the beginning or end of the lateral occurred (Figure 3). Average WAU for these emitters at this low head ranged from 0.603 (emitter D044) to 0.845 (emitter D015). A similar curvilinear relation between *q* and D was also noted for two emitters (D013 and D043) at 5.5 ft. of head but calculated WAU for these two emitters were 0.936 and 0.956, respectively.

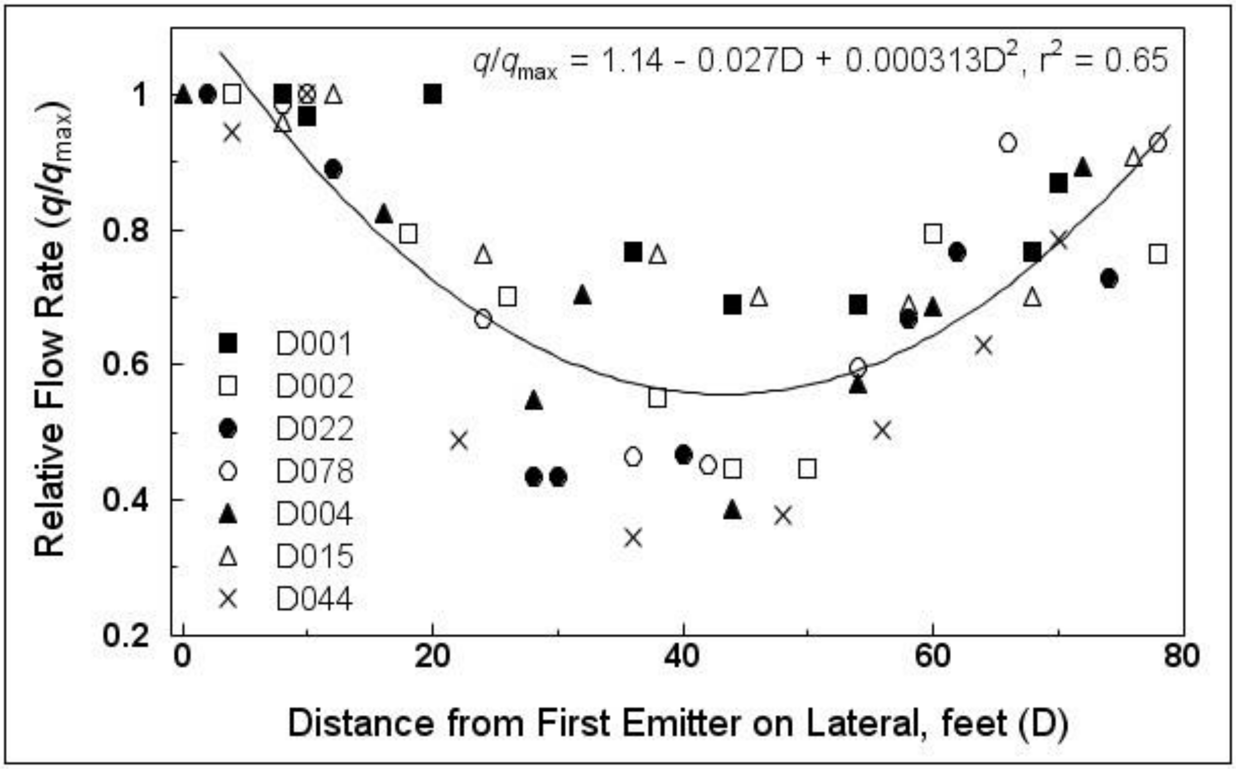

Figure 2. **Relative emitter flow rate (q/qmax) with distance (D) of seven emitters exhibiting a significant curvilinear relationship between q and D at a head of 3.5 feet.**

Emitter Evaluation at 25 psi

Average *q* at 25 psi ranged from 0.56 gph from emitter D079, a 0.5 gph, PC, self-cleaning emitter, to 7.15 gph from the Orbit 4G emitter, a 4.0 gph, NC, flag type (Table 3). These rates were 112.5 and 178.8 % of MSFR, respectively (Table 3). Average *q* from all PC emitters was 112 % of MSFR while that of the NC emitters was 180 % of MSFR. The average measured *q* from only three emitters, two Katif style (D043 and D045) and a 3.3 gph button style (D004) was 5% or less different than the MSFR. WAU was greater than 0.90 for fifteen emitters at 25 psi and for 11 emitters at 5.5 feet of head. Self-cleaning, PC emitters (e.g. D079 and D080) had *q* similar to MSFR and WAU greater than 0.90 at a pressure of 25 psi but did not flow at 5.5 feet of head (Table 3). These self-cleaning types, as well as anti-drip type emitters, apparently have diaphragms that cut off flow at a minimum threshold pressure. The WAU of five emitters (D045, D021, Orbit 1G, D077, and D076) was less than 0.90 at both 5.5 ft. of head and 25 psi (57.7 ft.).

Table 3. Average measured flow rate (q)[a], as gph and as % of manufacturer's specified *q* (MSFR), and water application uniformity (WAU) for 20 different point source emitters at 25 psi and 5.5 ft. of head. 2012.

Emitter[b] (part no.)	25 psi (57 Feet of Head)			5.5 Feet of Head		
	Q (gph)	% MSFR	WAU	Q (gph)	% MSFR	WAU
D080[c]	1.10	109.6	0.979	-	-	-
D015	1.98	198.0	0.974	0.210	21.0	0.954
D012	1.69	168.6	0.963	0.172	17.2	0.941
D004[c]	3.13	95.0	0.956	0.760	23.0	0.925
D022	3.86	192.9	0.950	0.222	11.1	0.825
D013	3.39	169.4	0.949	0.354	17.7	0.936
D002[c]	2.25	112.3	0.947	0.890	44.5	0.928
D044[c]	2.33	116.4	0.943	1.124	56.2	0.928
D078[c]	5.55	138.7	0.923	2.152	53.8	0.828
D079[c]	0.56	112.5	0.921	-	-	-
Orbit 4G	7.15	178.8	0.918	0.791	19.8	0.957
D043[c]	3.26	98.7	0.913	0.475	14.4	0.956
D001[c]	1.07	106.5	0.909	0.447	44.7	0.946
Orbit 2G	3.33	166.6	0.909	0.435	21.7	0.933
D006[c]	1.07	107.4	0.909	0.442	44.2	0.948
D045[c]	0.95	94.9	0.896	1.018	101.8	0.855
D021	1.80	180.0	0.880	0.075	7.5	0.893
Orbit 1G	1.87	186.8	0.835	0.305	30.5	0.774
D077[c]	2.88	143.9	0.777	0.775	38.8	0.376
D076[c]	1.07	106.8	0.767	0.377	37.7	0.897

[a] Flow rate values represent the mean of eight replications.
[b] Ordered from highest to lowest WAU at 25 psi.
[c] Indicates pressure compensating emitter

Summary and Conclusion

To irrigate efficiently, and provide garden or landscape plants with the volume of water they require for adequate growth or quality, the microirrigator must know the *q* and WAU of the selected emitter. If irrigating with both low pressure (i.e. rainwater catchment) and high pressure (i.e. household water tap) systems, the selected drip emitter should exhibit high WAU at variable pressure, and have a *q* at the low head sufficient to satisfy the peak water requirements of all plants in the management time frame. In this study, more than half of twenty point source emitters evaluated exhibited at least marginal (ASABE Standard, 1988) WAU (> 0.90) along a relatively short lateral (80 feet) at both

25 psi and a low, substandard head of 5.5 ft. As should be expected, *q* of most PC emitters was similar to MSFR at 25 psi and *q* of NC emitters increased or decreased with pressure. At 5.5 ft. of head, *q* of all emitters (PC and NC) except one (D045) fell below MSFR (emitter D045 has a self-flushing mechanism that allows more flow at pressures below 4 psi). When head was decreased to 3.5 feet, average *q* (of all emitters combined) decreased by more than 50 % (from *q* at 5.5 ft.) and only two emitters had an average WAU of greater than 0.90 (D013 and D043).

In conclusion, this preliminary study showed that point source microirrigation can be an effective method of distributing water to plants in small gardens or landscapes at substandard pressures if the correct emitter is chosen. Because of the sensitivity of *q* to even slight changes in head at these low pressures however, actual *q* and WAU of the chosen emitter(s) should be measured on site during initial system operation prior to developing irrigation scheduling programs. Further studies should evaluate *q* and WUE of emitters at different heads, lateral lengths, closed-loop configurations, etc.

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MAPPING TURF EVAPOTRANSPIRATION WITH HIGH-RESOLUTION MULTISPECTRAL AERIAL IMAGERY

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Abstract. Multispectral imagery with visible, near-infrared, and thermal wavebands was used to spatially estimate evapotranspiration (ET) in Berthoud, CO. The METRIC (Mapping Evapotranspiration at high Resolutions with Internal Calibration) energy balance model was used to estimate turf evapotranspiration from aerial multispectral imagery collected in 2011. The METRIC model was developed using Landsat satellite imagery but is adaptable to other satellite imagery with similar wavebands available. The METRIC model was also recently adapted for aerial imagery with limited reflective bands and a thermal band.

Following adaptation for aerial imagery, the METRIC daily ET for turf at Berthoud, CO was compared to daily ET from 44 mini-turf weighing lysimeters on 31 August 2011. Combinations of ETo (short crop or grass reference ET) vs. ETr (alfalfa or tall crop reference ET) and alfalfa vs. turf cold pixel resulted in mean percent error of 6.20 and 6.48%, for ETo and turf cold pixel and ETo and alfalfa cold pixel, respectively. METRIC agreement with lysimeter data using ETr as the reference ET ranged from 37.5% to 48.5% mean percent error for turf and alfalfa cold pixels, respectively. On 19 July 2011, mean percent error of METRIC ET and lysimeter ET using ETo and a turf cold pixel was 6.15%. METRIC applications for turf require ETo as the reference ET in the model.

Keywords.

INTRODUCTION

METRIC (Mapping Evapotranspiration at High Resolution using Internal Calibration) is a remote sensing model to estimate evapotranspiration (Allen et al. 2007b, c). METRIC has its roots in the SEBAL (Surface Energy Balance Algorithm for Land) model (Bastiaanssen et al. 1998a, b)

METRIC was developed as a method to estimate ET in irrigated agricultural regions from Landsat imagery. One strength was that it eliminated the need for a crop classification as it was based on well-established physical and biological parameters derived from the image bands and on-the-ground meteorological data. Recommendations for use included choosing a “cold” pixel that was part of a tall crop population. “Cold” pixels then assumed the value of 1.05x the tall crop, or alfalfa, reference ET value (ETr). For agricultural applications, ET is usually referenced to “tall” crop reference evapotranspiration (ASCE-EWRI, 2005), which is considered comparable to alfalfa reference evapotranspiration.

As METRIC applications have expanded, some potential limitations of the method have been encountered. Using multispectral aerial imagery, Chavez et al. (2012) found that using ETo (grass or short crop based ET) instead of ETr in a METRIC estimation in an advective environment improved agricultural crop ET agreement with lysimeter values. Also, in that study, alfalfa or other tall crop pixels were not cooler than grass (short crop) pixels in the limited aerial imagery frame and were not selected as the cold pixels.

On three dates in 2011, multispectral aerial imagery was acquired over Northern Water’s Conservation Gardens in Berthoud, CO. The purpose of this paper is to compare turf mini-lysimeter ET to METRIC ET with various combinations of ETr, ETo, and alfalfa vs. turf cold pixel. Results of the comparison will be used in future analysis of turf ET at the Conservation Gardens site. Because full cover alfalfa or other tall crop fields were not consistently available in the extent of the aerial image, it was imperative to verify that turf, the main subject of the aerial campaign, could be used as a reference for the cold pixel, and to verify whether ETr or ETo was the appropriate reference ET value to use in METRIC. Turf ET is typically referenced to ETo, so it is consistent to attempt to use that value in a METRIC turf analysis.

MATERIAL AND METHODS

Imagery

Multispectral aerial imagery was acquired on 19 July, 12 August, and 31 August 2011 via the Utah State University airborne multispectral remote sensing system (Chavez and Taghvaeian, 2012). Table 1 shows time of acquisition (Chavez and Taghvaeian, 2012). Flight and camera details are also found in Chavez and Taghvaeian, 2012. Reflective band resolution was 0.2 m and thermal band resolution was 0.6 m.

Table 1. Image acquisition times (24-hr basis, Mountain Standard Time).

Date	Morning flight	Afternoon flight
19 July 2011	1131	1327
12 August 2011	1055	1242
31 August 2011	1045	1347

The aerial imagery was georegistered and radiometrically corrected. Reflectance panels were used to calibrate the reflectance bands. Minor adjustment of pixel alignment among image dates and thermal and reflectance bands standardized the images for subsequent GIS analysis.

Only the 31 August 2011 morning image was used in this analysis, as full cover alfalfa was present in the image only on that date. The afternoon flight on this date had significant cloud cover. Lysimeter and METRIC analysis from 19 July 2011 were used to independently check the model and parameters generated from 31 August 2011. The lysimeters were hand-watered during the day on 12 August 2011, so lysimeter data were not available for that date.

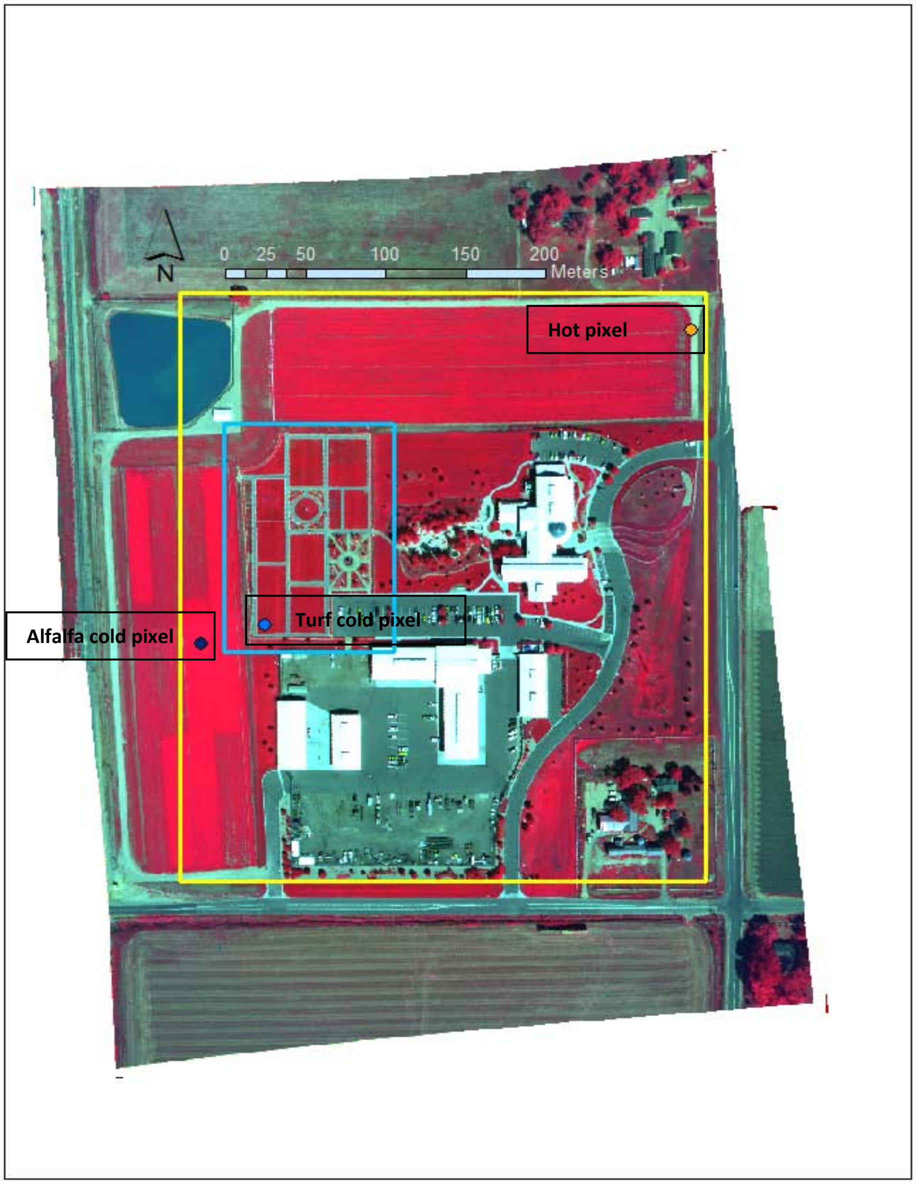

Figure 1. Aerial false color image on 31 August 2011 of Northern Water's property near the Conservation Gardens are outlined in blue. The clipped image is outlined in yellow. The alfalfa field in the analysis is located to the west of the Conservation Gardens. The cold and hot pixels are labeled in the figure.

METRIC

Details of the METRIC model are found in numerous references (Allen et al., 2007a, b, c). Conceptually, METRIC calculates ET via energy balance algorithms based on short wave reflective and thermal waveband imagery, such as Landsat satellite images. The energy used for evapotranspiration is calculated as a residual of net radiation minus soil heat flux and sensible heat flux. Because the remotely sensed data are indicative of current crop status and the algorithms are based on well-established physical processes, METRIC provides a direct method of calculating ET.

While METRIC was originally developed with Landsat satellite imagery, recent applications of the model used aerial imagery and were adapted for the more limited wavebands of the aerial data (Chavez et al., 2012). In the Northern Water application, modifications were also made to accommodate the limited spectral bands of the aerial imagery.

In this application, METRIC surface albedo calculation was modified for the limited band aerial imagery following concepts and procedures in Tasumi et al. (2008), the METRIC manual (Allen et al. 2007a), and in (Brest and Goward, 2007). Atmospheric correction was based on SMARTS2 (Gueymard, 1994, 1995) output for each date and image acquisition time, following concepts in Tasumi et al. (2008) and Allen et al. (2007a).

Also in this analysis, the SAVI (Soil-Adjusted Vegetation Index, Huete, 1988) L factor (the soil-brightness adjustment factor) was set at 0.05 after testing with various values of L. As L approaches 0, the SAVI becomes equivalent to NDVI, the Normalized Difference Vegetation Index (Rouse et al., 1973). Allen et al. (2007a) recommended L = 0.1 for Idaho conditions.

The cold pixel was selected from coldest turf pixels in the Conservation Gardens and coldest alfalfa pixels in the west alfalfa field. The hot pixel was selected from the limited range of bare soil pixels in the image, primarily from the east or north edges of the north alfalfa field, where there is a narrow soil roadway and a narrow transition from field to roadway. A simple daily soil water balance was used to estimate ET of the bare soil so that $H = RN - G - ET_{\text{bare soil}}$.

To maintain consistency with the chosen reference ET methods, EToF and ETrF were used to extrapolate the instantaneous METRIC ET values to daily ET values. EToF and ETrF are the instantaneous fractions of calculated actual ET to reference ET. EToF and ETrF are assumed to be relatively stable throughout the day.

Weather data

Weather data necessary for input into the METRIC model were obtained from Northern Water's Berthoud weather station, sited in the center of the Conservation Gardens. The weather station is maintained regularly and instrumentation checked or calibrated at least annually. More information about Northern Water's weather network, reference ET calculations, equipment,

operating standards, and sites can be found here:
http://www.northernwater.org/WaterConservation/BackgroundInfo.aspx.
Northern Water uses the ASCE-EWRI Standardized Reference methods (ASCE-EWRI, 2005).

Lysimeters

The 44 small turf weighing lysimeters were installed in 2009 and turf established in 2010, with 2011 the first full year of operation. Four replications with 11 turf mixes or blends were irrigated as for high quality turf. Briefly, lysimeters were 0.61 m deep, and 0.3 m in diameter, filled with a sandy loam soil. Each lysimeter was centered in a 1.22 m x 1.22 m plot of the same turf. The plot was large enough to have thermal pixels fully within the plot bounds. Areas within each lysimeter plot were digitized on pixel bounds for pixel data extraction in each plot area.

Weighing load cells were electronically logged at 15 min intervals. Details of construction and the first two years of the lysimeter study can be found in Crookston and Hattendorf (2012).

Irrigation was scheduled by soil water balance from the adjacent Berthoud weather station. A base irrigation was applied, and individual lysimeter plots were then hand-watered up to each individual lysimeter irrigation specification for that date.

Irrigation

The west alfalfa field was irrigated on several dates in 2011 (Figure 2). The cold pixels were located in a plot that was part of an alfalfa irrigation study. This plot was watered once after 1st cutting, with no irrigation after 2nd cutting. Irrigation resumed after 3rd cutting. This plot had temperatures consistent with temperatures in full irrigation plots, which could not be included in the clipped image.

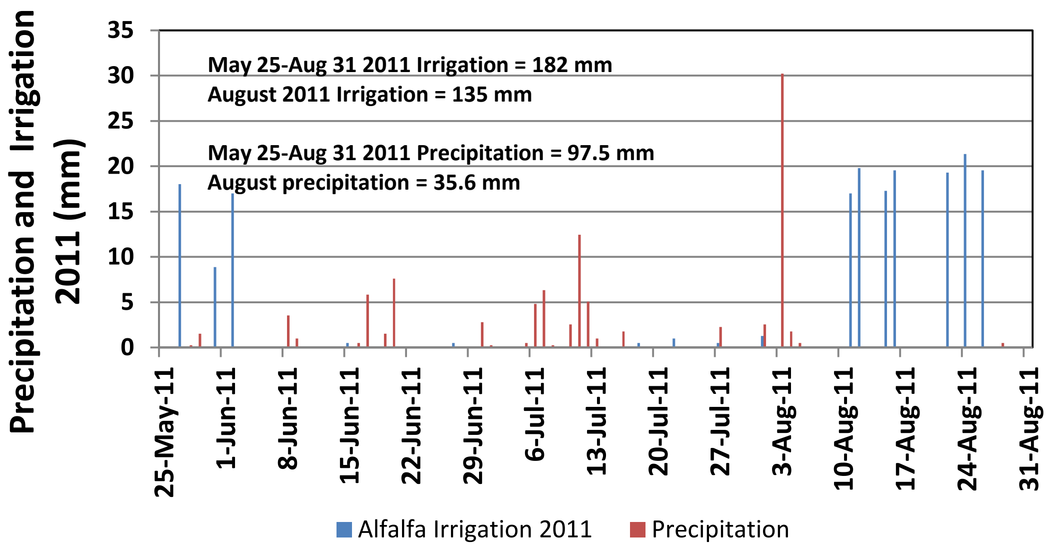

Figure 2. Precipitation and irrigation in the alfalfa plot where the alfalfa cold pixel was selected. The lysimeters were irrigated 6 days prior to the 31 August flight.

GIS was used to extract individual lysimeter METRIC ET values for comparison to the weighing lysimeter data. Only data from 31 August, 2011 were used for these comparisons, as that was the only date from the three flights that had full cover alfalfa. All rainfall, sprinkler irrigation, and hand irrigation in the lysimeters from 1 April 2011 to 26 Oct 2011 are shown in Figure 3.

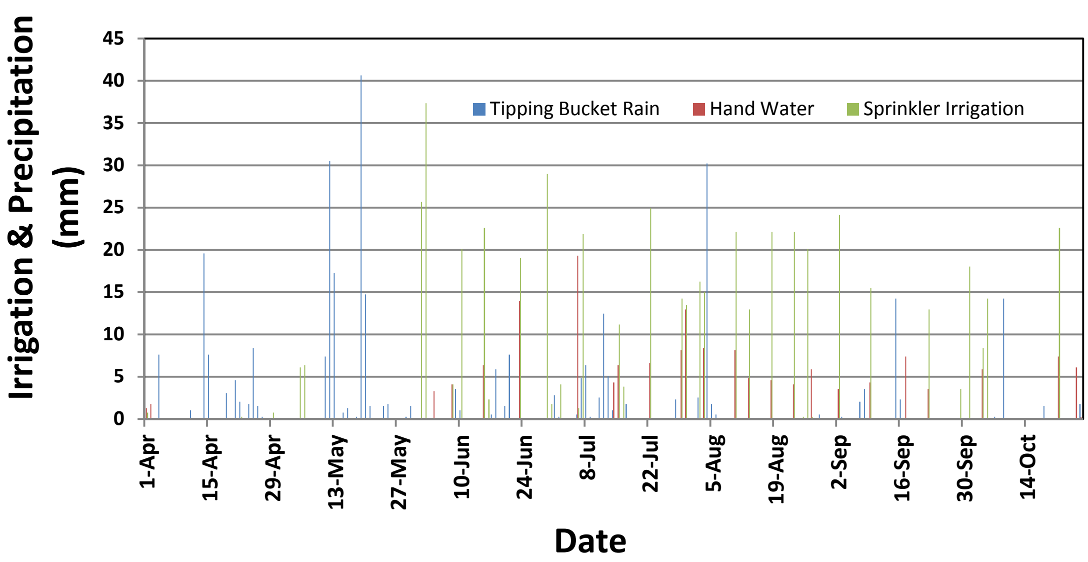

Figure 3. Lysimeter rainfall, sprinkler irrigations, and hand irrigations in 2011. Hand irrigations usually followed the base irrigation.

RESULTS

METRIC Analysis

The METRIC analysis was executed with the following cold pixel parameters (Table 2) with ETr and subsequently ETo as the reference ET used in METRIC. Each value was extracted with GIS analysis at the cold pixel point. The parameters are NDVI; LAI, leaf area index; Ts, surface temperature (deg K), and albedo. NDVI is calculated as (near-infrared [Band 4] – red [Band 3])/([near-infrared [Band 4] + red [Band 3]), with band numbers referenced to Landsat bands. NDVI is an indicator of green biomass—the higher the value, the greater the green biomass. Leaf area index is a dimensionless number commonly defined as area of leaves per unit area of ground surface. Surface temperature Ts (deg K) is obtained from the thermal band of the imagery product. Albedo is the unit less integrated surface reflectance across the full shortwave spectrum.

Table 2. Alfalfa and grass cold pixel parameters.

Cold pixel	**NDVI**	**LAI**	**Ts (deg K)**	**Albedo**
Turf	0.839	3.8	302.81	0.190
Alfalfa	0.896	5.7	299.22	0.282

Results of the METRIC analyses showed that using ETr with an alfalfa cold pixel overestimated ET values with a mean percent error of 48.54. Root Mean Square Error (RMSE) was 2.89. Error associated with all combinations of reference ET, date, and vegetation of cold pixel is listed in Table 3.

Table 3. Error associated with METRIC agreement with lysimeter data.

Date	Reference ET	Cold Pixel Vegetation	Mean % Error*	RMSE*
31August 2011	ETo	alfalfa	6.48	0.48
31 August 2011	ETo	turf	6.20	0.47
31 August 2011	ETr	alfalfa	48.54	2.89
31 August 2011	ETr	turf	37.46	2.24
19 July 2011	ETo	turf	6.15	0.42

*Mean % error = $[\sum(abs(y_{MET}-y_{LYS}))*100]/n$ RMSE= $\sqrt{[\sum(y_{MET}-y_{LYS})^2/n]}$
($_{MET}$ = METRIC; $_{LYS}$ = Lysimeter)

Although the alfalfa cold pixel was 3.59 deg C cooler than the turf pixel, this was less important to the accuracy of the METRIC analysis than the choice of grass or alfalfa reference ET. METRIC and its parent model, SEBAL, both use a scaled dT function and thus escape the limitation of using explicit surface temperature as a driver for ET (Allen et al. 2007b, Bastiaanssen, 1998a).

The upper and lower limits of evapotranspiration are effectively set by the reference ET and the multiplier chosen, in this case ETr x 1.05 or ETo x 1.05.

The reference ET places a limit on the range of ET values that can be generated from an analysis, regardless of the cold pixel temperature. Choice of ETo over ETr effectively muted the maximum ET that could occur with the given parameters even for a substantially cooler pixel.

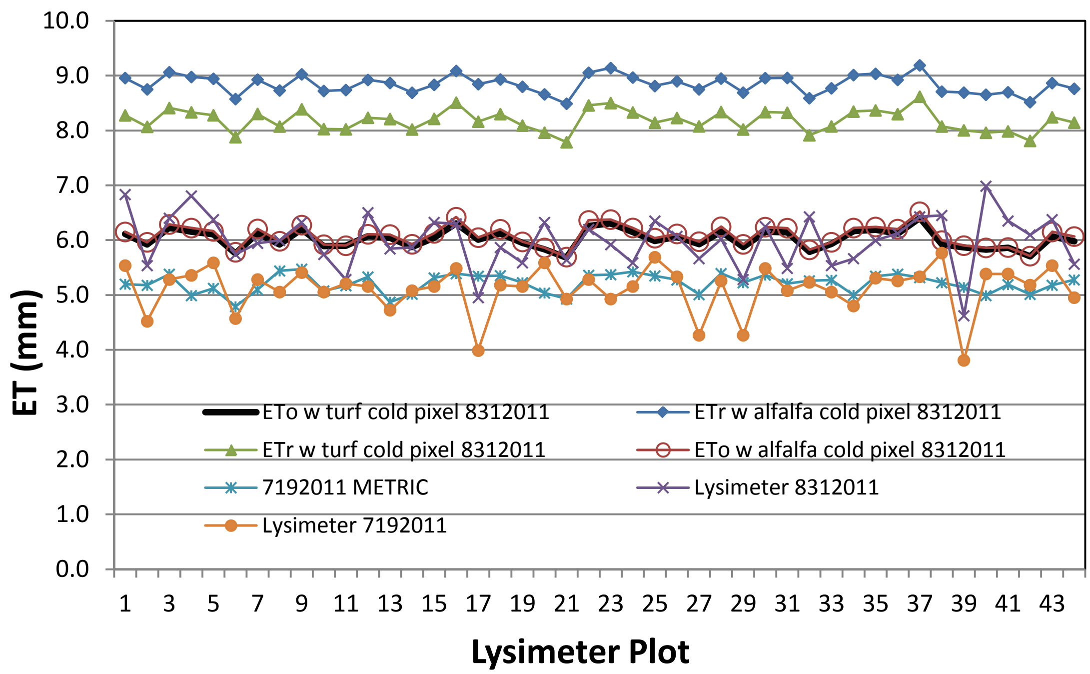

Figure 4. Extracted METRIC data points and the lysimeter data for 2 dates in 2011.

ETr with an alfalfa cold pixel systematically overestimated the 31 August 2011 lysimeter values (Figure 4). Choosing a turf cold pixel improved the estimate slightly, but METRIC still overestimated lysimeter ET. Standardized reference ET (ASCE-EWRI, 2005) is calculated at Northern Water; the separate calculations for “tall” crop and “short” crop were intended for the agriculture and landscape communities, respectively. It is clear from the results that a landscape turf application requires use of “short” crop reference ET.

Lysimeter ET for plots 17, 27, and 39 were lower than most of the other plots on both dates. These lower values were not well-tracked by METRIC. The turf in these plots (Ephraim Crested Wheatgrass) did not establish well. A factor that may have contributed to this non-agreement could be choice of SAVI L value. For this analysis, L = 0.05 yielded parameters within bounds of possible and appropriate values. This L value was more consistent with the recommended L value of 0.1 for Idaho conditions (Allen et al., 2007a) than with the original recommended L value of 0.5 (Huete, 1988).

Testing L = 0.5 led to daily ET values distant from the lysimeter values and implausible intermediate values of LAI and albedo in particular. However, further sensitivity analysis with the SAVI L value could establish a range of conditions, inputs, and plausible values. Other means of deriving the L factor, such as via MSAVI (Qi et al, 1994) might provide a more robust methodology, though this requires development of a soil line from the red and near-infrared bands. However, for specific sites, this might not be overly burdensome, if the procedure works.

There may be other factors that weigh into lack of agreement of the METRIC-calculated Ephraim Crested Wheatgrass ET with lysimeter ET, but because L was extensively tested over a range of values for this analysis, further refinement in selecting this factor may be necessary.

CONCLUSIONS

Expanding applications of METRIC create challenges in choice of reference ET and cold pixel selection. METRIC must be run with ETo as the upper limit for turf applications, at least for the ASCE-EWRI ETo formulation. Using ETr as the upper limit generated METRIC ET much higher than lysimeter ET. It is therefore consistent to search for a well-watered turf cold pixel, but in this analysis, it worked nearly equally well to choose a cooler alfalfa pixel. ET even from a colder pixel than in well-watered turf is constrained by the ETo*1.05 ceiling.

When using ETr, separation of the alfalfa and turf cold pixel ET estimates are spread apart because ETr embraces the full range of ET available to the agricultural or turf world.

This is apparently a limitation of METRIC: while a crop classification may not be genuinely necessary in most contexts, regional ET where there are large acreages of turf or sod farms may be significantly overestimated. By extension, ET of “short” crops with leaf area index or aerodynamics similar to turf may also be overestimated.

Potential limitations of this application may include methods of selecting the SAVI L value. In this analysis, the METRIC ET output could be verified against the lysimeter ET after testing a range of L values. However, most applications will not have this level of validation available. Experimentation with various suggested SAVI L values, such as L = 0.5, yielded ET and other parameters out of bounds of established typical values. It may be worthwhile to explore different methods of acquiring an L value, such as MSAVI.

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Making Sense of ET Adjustment Factors for Budgeting and Managing Landscape Irrigation

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Abstract. *Landscape water budgeting and conservation are central to many urban development programs and codes, water purveyor delivery and pricing policies, and professional landscape irrigation management practices. These programs, policies, and practitioners often use various approaches to calculate and establish a site's water-conserving irrigation budget and irrigation schedules based in part on estimated local reference evapotranspiration (ET_o) data. These calculations can involve an assortment of ET_o adjustment factors associated with plant species, site characteristics, or other influences on how much water a landscape requires or should be allocated. Depending on the formula used, the adjustments to ET_o can be fixed, variable, or some combination. Science in landscape plant water requirements and plant ecology shows it is illogical to apply guesstimated user-selected ET_o adjustment factors for microclimate and plant density or to use a species-specific plant factor (PF) to adjust ET_o that are derived from non-scientific data bases. Rather, research shows that a distinct PF applies to each of the following plant type groups: turfgrass; trees, shrubs and groundcovers; annual flowers; herbaceous perennials; and desert plants. Except where there are microclimate influences that can be quantified scientifically to be significantly different from the location where ET_o is calculated, a landscape water requirement can be simply yet effectively estimated by applying just the appropriate research-based plant-type PF's, such as follows: Gallons of Water = ET_o (inches) × PF (fraction) × Landscape Area (square feet of plant type) × 0.62.*

Keywords: crop coefficient, evapotranspiration, plant factors, landscape coefficient, landscape water conservation, plant water requirements.

Background and Introduction

Many green building programs, water conservation programs, local development codes, and water conservation ordinances along with delivery and pricing policies of many water purveyors employ calculations using estimated local reference evapotranspiration (ET_o) data to establish climate-based maximum and conservation levels of landscape water requirements or allocations (California Department of Water Resources, 2009, 2010; Eastern Municipal Water District, 2013; U.S. Environmental Protection Agency, 2009, 2010; U.S. Green Building Council, 2009, 2013). Landscape water managers often follow a similar approach to estimate landscape water requirements, water budgets, or irrigation schedules for sites they oversee. Sometimes equations used by green building programs, development codes, and water purveyors to establish a maximum water allocation or water budget for a landscape use only arbitrary, predetermined ET_o adjustment factors of 0.45 to 1.0 (Eastern Municipal Water District, 2013; U.S. Green Building Council, 2013). More commonly, the formulae used by these entities and landscape water managers to derive landscape water requirements and budgets include the use of a plant factor (PF) or a crop coefficient (K_c) to adjust ET_o in order to account for the variability in water requirements among landscape plant species. Such an equation is:

$$\text{Gallons of Water} = ET_o \times PF \text{ or } K_c \times \text{Landscape Area} \times 0.62,$$

where ET_o is inches of water for the time period of interest (day, week, month, year), PF or K_c are assumed by the user or taken from an accepted reference, landscape area is square feet of planted area, and 0.62 is a unit conversion factor to result in gallons.

In many instances, the required equation goes further and substitutes a so-called landscape coefficient (K_L) in place of the PF or K_c value as a means of adjusting ET_o. The equation using K_L for calculating a water allocation, requirement, or budget of a landscape area for a given period of time is:

$$\text{Gallons of Water} = ET_o \times K_L \times \text{Landscape Area} \times 0.62.$$

The K_L must be calculated separately with the following equation:

$$K_L = K_s \times K_{mc} \times K_d,$$

where:

- K_s is a plant species factor to account for the variability in water requirements among landscape plant species and is assumed by the user or taken from an accepted reference.
- K_{mc} is a microclimate factor, usually ranging from 0.5-1.4, assigned by the user to account for the presence of extreme meteorological conditions in a landscape (e.g. extreme reflected heat, persistent windy conditions, shade).
- K_d is a density factor, usually ranging from 0.5-1.3, assigned by the user to account for the presumed influence of layered canopies or closeness of plant groupings.

Although the K_L theory was conceived over 20 years ago and updated more recently (Costello, 1991; Costello et al., 2000), it has never been scientifically verified that the values produced by the K_L equation adjust ET_o to accurately and reliably reflect the amount of water landscape plants require to provide acceptable appearance and function. In fact, research in landscape plant water needs and plant ecology over the past 20 years or so indicates that using K_L to adjust ET_o adds unscientific complexity that does not result in greater accuracy in estimating the amount of water a landscape requires to provide acceptable performance and function.

Plant Factors

Research has demonstrated that water requirements of landscape plants are effectively defined as the percentage of ET_o (Allen et al., 2005) required to maintain their acceptable appearance and intended landscape function (Pittenger et al., 2001; Shaw and Pittenger, 2004). The ET_o calculation assumes the following standard conditions for a hypothetical cool-season turfgrass reference surface: a uniform plant canopy growing in full sun that covers at least 75% of the soil surface and that governs how foliage connects to the atmosphere, uniformly adequate soil water, and plant water use that is tightly synchronized and linearly related with changes in ET_o (Allen et al., 2005). The ET_o algorithm was developed for agricultural crop production systems, and a crop's estimated requirement is the product of ET_o x a species-specific fraction that is the estimated depth of water the crop requires to provide optimum growth and yield. The species-specific fraction for this purpose is known as a crop coefficient (K_c), and it assumes all the standard conditions for calculating ET_o are present in the cropping system.

The ET_o x species-specific fraction algorithm has limited accuracy in estimating water needs of urban landscapes, however. The algorithm is not robust enough to account for the spatially and biologically complex mixes of turfgrass, woody, and herbaceous plants that comprise urban landscapes (St. Hilaire et al., 2008). These plant types differ in canopy architecture, plant structure, and leaf size in ways that do not conform to the standard conditions under which ET_o is calculated and defined. Water requirements of many non-turf landscape plant species are not tightly synchronized to ET_o and may respond non-linearly to climatic factors used to estimate ET_o (Choudhury and Montieth, 1986). Also, unlike agricultural crops, urban landscape plants are grown for their aesthetic appearance and functional value that can be achieved over a range of water application amounts, rather than optimum growth and yield based on precise water application requirements.

Nevertheless, the approach of estimating landscape plants' water requirements as a percent of ET_o using an adjustment factor [plant factor (PF)] is rational, reasonable, scientific, and climate-based (Kjelgren et al., 2000; Snyder and Eching, 2006). This approach is sufficiently accurate and effective in estimating landscape water requirements based on a given plant palette. Understanding the limitations of ET_o x PF, however, is crucial to success when estimating landscape water requirements and managing landscape water for the range of different landscape plant types that occur.

Perhaps the mostly widely referenced source of species-specific PF values for landscape plants is the California-based Water Use Classifications of Landscape Species (WUCOLS) list (Costello and Jones, 2000), which refers to these values as a "species factor", K_s . The WUCOLS values for PF's range from <0.1 to 0.9, and it arbitrarily ranks PF values into ranges of high, medium, low, and very low water use. It is available online and provides a large number of specific PF's needed to fulfill the landscape water requirement and water budget calculations mandated in many water conservation ordinances in California (California Department of Water Resources, 2009, 2010). It also appears that PF's in WUCOLS are the basis for the PF data bases and ranges included in many other local and national green building and water conservation programs (Dukes, 2008; U.S. Environmental Protection Agency, 2009, 2010; U.S. Green Building Council, 2009, 2013). Unfortunately, the WUCOLS content is not scientific and is not research-based. The data can be unreliable when compared with research-based findings of landscape plant water needs (Martin et al., 2010; Oki and Reid, 2009; Pittenger et al., 2001, 2002, 2009; Shaw and Pittenger, 2004).

Turfgrass. Estimating water needs and managing irrigation of turfgrass as a percentage of ET_o ($ET_o \times PF$) is a demonstrated effective approach because turfgrass swards closely mimic the standard conditions of ET_o estimation (Richardson et al., 2013; Devitt et al., 1992; Gibeault et al., 1990). Because turfgrass synchronizes well with ET_o and it is usually expected to have meaningful growth and yield (clippings), its species-specific water requirement as a fraction of ET_o is actually a K_c. The research findings indicate that the average K_c for cool-season turfgrass is 0.8 and the K_c for warm-season grasses is 0.6. These factors provide good quality general turf, but are not adequate for turf grown in sports fields or golf courses.

Trees, Shrubs, Groundcovers. The ET_o x PF approach has been shown to be an appropriate means of estimating water required ET_o by landscape groundcovers and shrubs to provide acceptable landscape performance (Beeson, 2012; Pittenger et al., 2001; Shaw and Pittenger, 2004; Staats and Klett, 1995; Sun et al., 2012). The approach can also be successful in estimating the amount of water required for landscape tree and shrub species to provide acceptable performance in most landscape settings, but a tree PF comes with somewhat less reliability (Costello et al., 2005; Pannkuk et al., 2010; Pittenger et al., 2002 and 2009).

A common finding among these studies is that tree, shrub, and groundcover species growing in arid climates with a relatively dry growing season (e.g. areas with Mediterranean climates and many portions of the southwestern and intermountain west U.S.) typically need water in the amount of about 50% of ET_o during the growing season in order to provide acceptable appearance and function. Thus, a PF of 0.5 incorporates the variable response to climate of many tree, shrub, and groundcover species, and potentially mild water stress that does not affect plant appearance and performance. However, a PF of 0.7 is more appropriate for woody plants and groundcovers growing in humid climates with relatively high summer rainfall, or for woody plants and groundcovers native to wet habitats (including riparian species in arid climates). Differences in water needs of an individual woody plant species in response to climate factors, particularly humid air, are less pronounced where sustained drought (plant-damaging water deficit) is not common and plant density is high (Jung et al., 2011).

Often trees in urban landscape settings are not in dense forest stands where much of a tree's crown is buffered by adjacent trees. The greater crown exposure and ventilation by wind means that an isolated tree is not buffered from climatic factors, and so it responds non-linearly to ET_o (Daudet et al., 1999; Goldberg and Bernhofer, 2008; Jarvis and McNaughton, 1986). Somewhat analogous to an electrical circuit breaker, this response is most pronounced in regions where the air is very dry (high ET_o) during the growing season and plant species respond by reducing transpiration at high ET_o (Schulz, 2003; Tardeiu and Simmoneau, 1998). For isolated urban trees, the plant's transpiring leaf area controls the volume of water required, so the ET_o × PF × Landscape Area approach must be modified to include an estimate of the transpiring leaf area (Devitt et al., 1994; Montague et al., 2004). In these situations, the plant factor of 0.5 or 0.7 still apply, but the procedure described below in "Landscapes with Incomplete Canopy Cover" should be followed to estimate water requirement of the landscape area.

Annual Flowers. Published scientific ET_o-based water requirement data is presently unavailable for annual flowering plant species. These plants have shallow root systems and are generally observed to have limited drought tolerance or resistance. Since they are expected to provide dramatic color and impeccable aesthetic appearance, a reasonable PF for their estimated water requirement is 0.8.

Herbaceous Perennials. Published scientific ET_o-based water requirement data is very limited for herbaceous perennial plants. Data available for a few herbaceous perennial plants is largely from species adapted to dry climates. It shows considerable variability among the few species evaluated, but it appears the species evaluated perform acceptably at 40-60% of ET_o (Oki and Reid, 2009; Reid et al, 2012; Sun et al, 2012). Since these species are usually expected to provide highly attractive flowering and/or foliage in the landscape, and most are adapted to mesic or moist habitats, a plant factor of 0.7 is reasonable for this plant group to assure performance expectations are met. See the discussions below for instances where an herbaceous perennial is a desert or native plant.

Desert Plants. There is no published scientific ET_o-based water requirement data for desert plants, and water requirements and PF's of desert plants are difficult to estimate. Most desert plants combine traits to reduce leaf temperature and stomatal opening that minimize transpiration, together with thick, evergreen leaves. Through various combinations of traits, these plants survive on very limited rainfall in their native climate, but they do not necessarily provide acceptable landscape appearance and function with this amount of water. The key to understanding desert plants is that most are perennials and shrubs, but few trees: the ecological answer is that trees have more leaves and so require more water than is available in desert habitats. A plant factor of 0.3 represents the estimated water required to ensure this plant group provides acceptable landscape performance.

Native Plants. Specifying a plant factor for native plants is difficult because native plants are by definition adapted to a specific region and climate. Published ET_o-based water requirement data for native plants is very limited and addresses largely plants native to Mediterranean (low summer rainfall) climates (Oki and Reid, 2009; Reid et al, 2012). Native perennial plants, regardless if they are woody or herbaceous, survive in landscapes with normal precipitation once they are established when grown in their native climate range. They may not provide acceptable landscape performance in such situations, however. Lacking significant data, it is reasonably estimated that PF's of native plants depend the plant type group presented above that a given species best fits.

Landscapes with Incomplete Canopy Cover. The ET_o × PF approach is most applicable in landscapes where plant canopy covers at least 75% ET_o of the soil surface and the plants are watered uniformly by irrigation or precipitation. In landscape plantings with less than 75% canopy coverage, such as newly planted landscapes where plant canopies are small and immature or established landscapes with widely-spaced isolated plant specimens, water needs become that of the individual plant, as discussed above. Plants in such landscapes are ideally drip irrigated based on volume of applied water rather than depth. The PF and uniform water application to the entire landscape area are less important than the size of the canopy (Beeson, 2010, 2012; Sun et al., 2012). These situations dictate estimating the canopy size (or total leaf area, which is difficult) of individual plants and then applying the appropriate PF.

The estimated PF for an irrigation zone or similar grouping of plants with similar water requirements and less than 75% canopy cover can be effectively adjusted by multiplying the PF by the percent canopy cover for the zone. Here, plant and landscape water requirements are estimated by multiplying the PF by the area of the crown projection of each plant to arrive at a volume of water:

$$\text{Gallons of Water} = ET_o \times PF \times (\text{Canopy Radius}^2 \times 3.14) \times 0.62.$$

Where the plants are widely spaced but have uniform canopy projections the average individual plant canopy cover area can be multiplied by the number of plants to obtain total canopy area.

Density Factor

A landscape density factor (K_d) included in the calculation of a K_L allows the user to apply a value usually from 0.5 to 1.3. To account for plantings that have incomplete canopies, a K_d value <1.0 is applied, and for plantings with layered or "closely spaced" canopies a K_d value >1.0 is applied (Costello et al., 2000; U.S. Environmental Protection Agency, 2009). The ET_o estimate assumes at least 75% canopy cover (closely spaced plant canopies), so applying a K_d value >1.0 is not defensible. When the canopy cover is <75%, ecological science supports following the approach outlined above under "Landscapes with Incomplete Canopy Cover" rather than applying a guesstimated ET_o adjustment via a K_d between 0.5 and 0.99. A layered landscape canopy, as when groundcover is grown under a tree canopy, does not significantly increase the water demand of the planting as the K_d adjustment in K_L presumes. This is because plant water use, and thus ET_o, are influenced most by the amount of solar radiation (sunlight) reaching the foliage and the exposure leaves have to the atmosphere; in layered canopies little light reaches understory foliage which is also highly buffered from the atmosphere, so the water use of the understory is negligible. Thus, K_d would not be >1.0 in these situations based on the ET_o algorithm and plant ecology principles.

Microclimate Factor

A landscape microclimate factor (K_{mc}) included in the calculation of a K_L allows the user to apply a value from 0.5 to 1.4 to account for plantings that experience extreme meteorological conditions, such as extreme reflected heat, persistent windy conditions, or shade (Costello et al., 2000; U.S. Environmental Protection Agency, 2009). Since an ET_o accounts for variations in meteorological factors affecting plant water use, applying an additional ET_o adjustment factor via K_{mc} is appropriate only in situations where one or more meteorological factors affecting a landscape are persistently and significantly different from those present at the location where ET_o is estimated. This could include constant daily high wind or continuous shade on a portion of a landscape cast by a tall building, for example.

There is no simple means for a user to effectively guesstimate a K_{mc} adjustment factor, however. The influence that microclimate conditions have on landscape plant water requirements can be empirically estimated over a considerable period of time. Alternatively, biometeorology principles and instrumentation can sometimes be employed to estimate the actual effect these extreme meteorological parameters have on ET_o, and then a specific adjustment can be made to the equation that calculates ET_o (R. L. Snyder, personal communication). Indeed, there are examples where use of meteorological instrumentation has been used to successfully modify ET_o estimates when locally persistent high wind conditions occur that are different than the wind occurring at the ET_o estimation site (R. L. Snyder, personal communication). This approach is scientifically valid and superior to applying a guesstimated K_{mc} of 0.5 to 1.4 and using the K_L equation to adjust ET_o. However, the actual effect certain extreme meteorological factors like reflected heat and shade actually have on the amount of water required by landscape plants to provide acceptable performance and function has not been determined scientifically, so the weighting of a microclimate adjustment to ET_o remains theoretical.

Conclusions

The ET_o algorithm has serious limitations in estimating the water requirements for non-turf landscape plants and entire mixed landscape plantings because it is not robust enough to account for the spatial and biological complexity that comes with urban landscapes. However, it is indefensible to apply arbitrary guesstimated adjustment factors K_{mc} and K_d to calculate a K_L, and/or adjust ET_o with a K_s or PF that is derived from non-scientific data bases such as WUCOLS. Such ET_o adjustment approaches are scientifically invalid, and they provide a false sense of precision and effectiveness while complicating the calculations for estimating landscape water requirements. Unfortunately, many of the green building and landscape water conservation programs and ordinances across the U.S. have adopted these approaches, so the merit and effectiveness of these measures in conserving water are questionable. Science in landscape plant water requirements and plant ecology suggest PF's for landscape plants are dependent primarily on what general plant type a given species fits, and ET_o can be simply and accurately adjusted to estimate landscape water requirements using these generalized plant-type PF's.

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Title: Stripped Down Water Management Practices with 24/7- 360 Degree Access

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1. Results
2. the idea that we need to do more to elevate landscape water management as an important part of managing water resources to property owners and utilities.

Abstract.
Current water management practices by landscape companies are in a defensive posture due to a lack of understanding a comprehensive water management approach and not fully grasping the business opportunity. This presentation will equip listeners and readers with insights on practices and online water management tools gained over the last 4 years in Southern California region (San Diego, Los Angeles, and Ventura) by a water management company that works closely with landscape contractors and water agencies. More comprehensive water efficiency methods as well as online water management tools will greatly enable our landscapers to succeed in practicing excellent water management. The shift in focus is to practice water management through data driven water budgets and use online tools to give all concerned parties 360-degree access. Return on investment calculations and real case studies will be shared.

Since 2012, twenty five commercial sites in Southern California have received water surveys from a water agency. A water survey consists of the following: Detailed outdoor survey of the irrigation system, creation of a site-specific water budget, maps if needed and a recommended irrigation schedule and enrollment in an online water management program.

The purpose of the water conservation program was to exploit ways to accomplish the following:
1. Lower outdoor water survey costs
2. Increase the expertise of surveyors
3. Increase the survey efficiencies by increasing the number of customers that were willing to implement significant retrofits per the survey recommendations
4. Make a change in landscapers approach to water management with a heavy emphasis on management systems and tools.

Current technologies have allowed water agencies and now landscapers to use online webbased water tracking tracking tools. Using these online tools as a a follow up process to surveys is a uniqure approaach in these markets (about 4 water agencies currently use this approach). These programs have a pathway for each client to participate in. Each of these steps can be scaled down for any landscape maintenance company and applied to their current client base.

Here are the program steps:
1. Identify top water savings potential users. Savings potential is determined by comparing the sites water usage history obtained from the water agency to the satellite area measurements and projected water budget. Water budgets are built on plant material area measurements.
In this case a landscape company could survey their clients and find the top water savings potential users and take the same approach.

2. For each client there is a "kick off" meeting. Participants are utility, vendor and customer. Key staff are present and great effort is made to get the true decision makers. Meeting identifies decision makers for retrofit or budget decisions or at bare minimum who will repair identified leaks and other repairs to improve efficiency.
This type of meeting also can occur for a landscape company in that when they approach the client for an irrigation efficiency project, they can ensure they have the right people at the kick off meeting.

3. A voluntary water budget is established during the survey (which confirms and modifies to make it more precise than from the satellite images) reflecting appropriate indoor and outdoor water requirements for a customer
a. Data is recorded on tablets versus paper for easier and faster processing.
b. Survey reports address the lowest hanging fruit in short concise reports rather than numerous pages of charts and pictures, and unnecessary details.
c. More emphasis is placed on a water management plan for the site-specific requirements than just reporting the site needs weather based irrigation controllers and nozzle rebates. The goal is to avoid just identifying leaks and sprinkler issues and get to the heart of building a site appropriate water management system.
Once again, this approach can be used by landscape companies. Taking their estimating system for irrigation efficiency improvement projects to the a more streamline approach. A clear focus on items that have a significant return on investment will sell more in the long run.

4. Budget is entered into the monitoring tools and monthly post survey water usage is measured against the established budget.
a. This tool is used by landscape water managers, water agencies, and property owners.
b. These online tools allows water agencies to monitor sites after a survey has been completed and compared to their historical usage. A program summary page shows the savings achieved for all sites enrolled. This is used to evaluate the effectiveness of the water conservation program.
For a landscape company they can manage their sites internally and publish the data to their clients on a monthly basis. This data can be incorporated into the invoices as well so the client sees the added value each month and gets that monthly "feeling" of savings and knowledge that their landscape company is watching over their water bills as much as they are.

5. If a customer's usage significantly exceeds his budget for that particular month the water agency staff or the survey vendor will contact the customer and discuss potential issues regarding

the high use. In the same manner if the customer's usage is below budget they are cheered on by a complimentary email.

a. Monthly e-mails are sent to the site owner and staff.

b. On site landscape water managers take action with knowledge of their water usage whether it is above or below the budget. It is also a rewarding opportunity for them to save water and money for their client and for all involved to be in the know.

c. The water conservationist at the agency can see all of their sites in their service area and quickly assess any problem sites. Performance is indicated by a red colored percentage over historical usage, a yellow colored percentage if under historical usage, and a green percentage if under budget. This creates a streamlined management dashboard to focus efforts on weak site performances.

In each of the online tools, the visual displays may differ, but the same message of water awareness is being communicated. A proactive landscape company can take an online water management tool and deliver great service to their clients versus waiting for the client to call about a high water bill.

6. Follow up meetings is scheduled with the same participants after the survey is completed to discuss results and further steps.

A landscape company can schedule quarterly meetings to review results in water savings for their clients and ensure them that this resource is being carefully handled.

Here are the results:
1. Positive feedback from customers
2. Has helped create a commitment from survey customers to follow up after a survey is conducted and reevaluate water efficiency practices rather than going back to status quo.
3. Highly effective in leading to a much closer customer- utility partnership for water efficiency improvements
4. Has led to significant capital investments from customers for improved water efficiency measures and some even beyond the survey recommendations. Here are two examples:

a. 8 acre High school in Ventura – purchased $22,000 for 2 wireless Rain Master controllers, (4 controllers total plus the 2 wireless with 95 stations) weather station and many miscellaneous cable, parts, software boards to tie all the controllers together. Plans are to go forward with more work and getting the system dialed in as far as using based scheduling. The high school staff is excited about saving water with these new tools.

b. 16 acre Cemetery in Los Angeles- Purchased and installed $30,000 worth of automated irrigation valves as well as 2 new controllers. They also retrofitted many of their rotors with the correct nozzle sizes.

5. Out of 25 sites that have participated in this program, approximately 50% have lowered their water consumption compared to their historical usage. Some sites have even lowered their consumption to remain under the established site budget.

Conclusion

This approach to water management has made a major impact in the commercial landscape industry for southern California. Each site has had engagement with the water agency in some manner. Awareness through online tools has been a real help to all involved. Further research will be conducted on finding optimal scheduling approaches that fit each landscape company and their level of expertise. Also mobile apps on smart phones are being incorporated. Water survey costs have been lowered and engagement for water savings actions has been increased.

Landscape companies can learn from this type of work in the water agency market. Water conservationists have a parallel role to a landscape water manager. Online tools, more emphasis on lowest hanging fruit for return on investment, and also not being afraid to take charge of water consumption is the new calling for our landscape water managers. Let's take that calling and run with it.

Effect of Irrigation Systems and Landscape Species on Irrigation Water Requirements Simulated by the Irrigation Management System (IManSys)

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Abstract. *Accurate landscape Irrigation Requirements (IRRs) determination is needed to help optimize landscape water use. Landscape evapotranspiration data are limited for many species, geographic locations, and for different irrigation systems. Efforts have been spent to determine values of landscape coefficient to estimate landscape evapotranspiration. IManSys, a water allocation model that uses specific edaphic parameters, weather data, and plant water use values was used to determine effect of different irrigation systems (drip, sprinkler and flood irrigation), and landscape coefficients on IRRs for different landscape mixtures under three major US metropolitan areas (Houston, Texas; Tampa Bay, Florida; and Honolulu, Hawaii). Weather data, soil physical properties, and values of landscape coefficients were used as input for IManSys to simulate irrigation water requirements for several major landscape mixtures. Rainfall and irrigation system efficiency are the major factors impacting IRRs followed by landscape coefficient, irrespective of the location. IManSys proves to be useful tool to determine and study IRRs under different conditions.*

Keywords. IRRs, IManSys, irrigation system, landscape

Introduction

Maintenance of landscape requires large amounts of water, particularly in areas with low rainfall. In fact, in urban environments of arid regions of the U.S., landscape irrigation consumes about 40% of all residential water use (Ferguson, 1987). Thus, proper system of landscape irrigation should be used to conserve water in landscaping. Proper irrigation system provides the right amount of water at the right time and place, for optimal growth of plants. Different irrigation systems are used to irrigate landscape planting. Trickle (drip) irrigation applies small volumes of water and can operate under low pressure. Drip irrigation is the most efficient and has become more popular for irrigating landscapes in and around urban centers. Sprinkler irrigation systems are used for turf areas, very large trees, and areas that require a high level of moisture, such as planter beds. Sprinklers are very inefficient, where large amount of water can be lost through evaporation and falling on non-targeted areas (e.g., roadways, sidewalks). Flood irrigation is a simple and cheap method that allows water to flow on the soil surface to where the plants are. Flooding provides deep watering; however, about one-half of the water usually ends up not getting to the crops and even some of the excess water washes away nutrient from the root zone. The selection of irrigation system depends on a number of factors, such as the size of the landscape area, landscape plant type, geographical location, underground utilities, and environmental regulations. Accurate landscape IRRs determination is needed to help optimize landscape water use. Thus, the main objective of this study is to determine the effect of different irrigation systems (drip, sprinkler and flood irrigation), and landscape coefficients on IRRs for different landscape situations in three metropolitan areas in Houston, Texas; Tampa Bay, Florida; and Honolulu, Hawaii using IManSys.

Materials and Methods

Study Area

This study was conducted in three major metropolitan areas in Houston, Texas; Tampa Bay, Florida; and Honolulu, Hawaii. Comparative climatic data for these three metropolitan areas (NOAA, 2013) are shown in Table 1. The annual average rainfall of Honolulu is comparatively lower, while its daily mean temperature is the highest amount these three areas.

Table 1. Comparative climatic data of three metropolitan areas (NOAA, 2013)

Metropolitan	Daily mean temperature (^oF)	Annual average rainfall (inch)	Annual average wind speed (MPH)	Annual average relative humidity (%)	
				Morning	Afternoon
Honolulu	77.7	17.1	11.2	71	56
Houston	69.5	52.7	7.6	88	70
Tampa Bay	73.4	46.3	8.3	86	58

A summary of selected climate stations, climate data range, soil type, hydrologic group and runoff curve number for these three metropolitan areas are shown in Table 2. The daily climate data of Waikiki (Station ID: GHCND:USC00519397) and Houston Intercontinental Airport (Station ID: GHCND:USW00012960) were downloaded from the webpage of National Climatic Data Center (NCDC) and the climate data for Balm (Station ID: 350) was downloaded from the Florida Automated Weather Network (FAWN) website.

Table 2. Summary of data

State	Location	Climate data	Soil type	Hydrologic group	Runoff curve number	Curve type and hydrologic condition
Hawaii	Honolulu	1965 – 2011 (Waikiki)	Kawaihapai	B	70	Residential districts by average lot size: 1/2 acre
Texas	Houston	1984 – 2010 (Houston IA)	Wockley	C	80	" "
Florida	Tampa Bay	2004 – 2011 (Balm)	Candler	A	54	" "

Irrigation Management System (IManSys) Model

Plant irrigation requirement is the amount of water, excluding rainfall that should be applied to meet a plant's water demand without any significant yield reduction. There are several models that have been used in plant water allocation, e.g., AFSIRS (Smajstrla, 1990), IManSys (Fares and Fares, 2012). IManSys is a numerical simulation model used to calculate IRRs for different plants. Irrigation requirements calculated using IManSys are more realistic for areas where runoff and rainfall canopy interception are dominants. In addition, it also includes other features such as evapotranspiration calculation using different models (e.g., Penman-Monteith Equation (Monteith, 1965), ETM (Fares, 1996), and Hargreaves-Samani Equation (Hargreaves and Samani, 1982)) with either complete daily weather data or just minimum and maximum temperatures.

IManSys has several databases of, e.g., soil and plant growth parameters, irrigation systems, canopy interception. IManSys was implemented in JAVA object oriented language. IManSys output includes detailed net and gross IRRs, and all water budget components at different time scales (daily, weekly, biweekly, monthly, and annually) based on non-exceedance drought probability which is calculated from a conditional probability model that uses the type I extreme value distribution for positive non-zero irrigation values (Fares and Fares, 2012).

IManSys model uses the water balance approach with a two-layer soil profile to simulate the irrigation water requirement for specific plants on a daily basis. The plant specific irrigation requirements are calculated based on plant physiology, soil, irrigation system, growing season, climate and basic irrigation management practice. The daily water balance equation for the soil column defined by the plant root zone expressed in terms of equivalent water depth per unit area (cm) is:

$$\Delta S = P + G_w + IRR_{net} - \left(Q_D + Q_R + ET_c + I\right) \quad (1)$$

where ΔS is the change in soil water storage expressed as equivalent water depth (cm), P is the gross rainfall (cm), G_w is the groundwater contribution (cm) from shallow water table, IRR_{net} is the net irrigation water requirement (cm), (Q_D + Q_R) is the summation of groundwater drainage and surface water runoff (cm), ET_c is the plant evapotranspiration (cm) and I is the canopy rainfall interception (cm).

The water storage capacity is amount of water that is available for plant uptake. It is calculated as the equivalent water between field capacity and permanent wilting point for a given soil multiplied by the depth of the root zone.

Thus, gross irrigation water requirement ($GIRR$) is calculated as follows:

$$GIRR = \frac{ET_c - \left(P + G_W - Q_R - Q_D - I\right)}{(1 - LR).f_i} \quad (2)$$

where f_i is the irrigation efficiency, and LR is the leaching requirement to avoid salt built up in root zone.

IManSys calculates runoff, drainage, canopy interception, and effective rainfall based on plant growth parameters, soil properties, irrigation system, water management practices and long-term weather data (rain, evapotranspiration, and temperature). The detail of model can be found in Fares and Fares (2012). In all locations, simulations were carried out using different landscape coefficients and three different irrigation systems (Multiple sprinkler, Trickle (drip), and Flood). Irrigation system application efficiency of multiple sprinklers, trickle (drip) and flood irrigation are 0.75, 0.85 and 0.5, respectively.

Landscape Coefficient

Crop coefficients used for agricultural crops and turf grasses are different for landscape. Crop coefficient does not consider the variety of species, crop density, and micro-climate. Landscape plantings are typically composed of more than one species. Vegetation density varies considerably in landscapes. Landscapes environment is heterogeneous; it is subject to a wide range of micro-climates that varies due to variable shading, wind, and relative humidity. The collective effects of all environmental factors make landscape plantings quite different from agricultural crops and turf grasses. Realistic landscape coefficients account for these differences (Costello et al., 2000). Estimation of water requirements of urban landscape plants using landscape coefficient was close to result of actual irrigation records (Nouri et al., 2013). Estimated landscape evapotranspiration (ET_L) is the product of reference evapotranspiration (ET_O) and landscape coefficient (K_L) as follows:

$$ET_L = K_L \times ET_O \tag{3}$$

The landscape coefficient is a function of species factor (k_s), density factor (k_d) and microclimate factor (k_{mc}) that vary between and within different landscape vegetation types:

$$K_L = k_s \times k_d \times k_{mc} \tag{4}$$

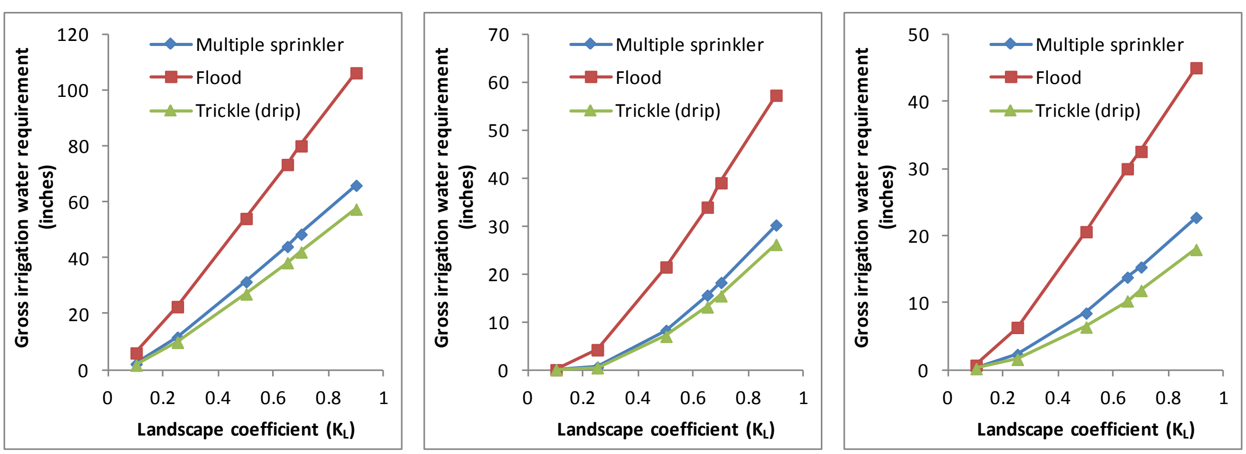
The reported ranges of different landscape coefficient factors can be as low as less than 0.1 and as high as 1.4 (Costello et al., 2000). Seven different cases of landscape coefficient were developed by combining three different landscape coefficient factors resulting in a landscape factor ranging between 0.1 and 0.9.

Results and Discussions

Gross irrigation water requirement

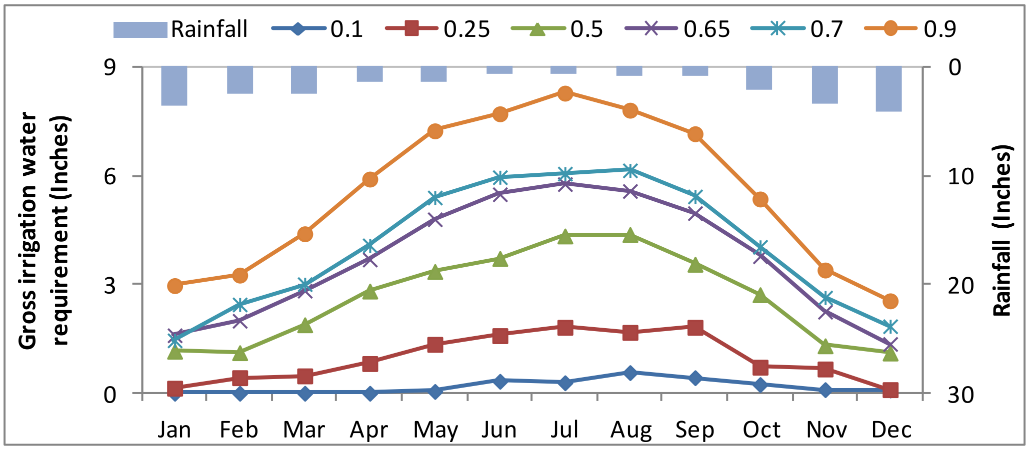
Gross irrigation water requirements (GIRRs) vary according to irrigation system (Fig. 1). Irrigation water requirement is higher for flood irrigation system compare to multiple sprinkler and trickle (drip) irrigation system. Flood irrigation system has lower irrigation application efficiency. Trickle (drip) irrigation system is much more efficient than flood irrigation system. When landscape coefficient is smaller the difference in irrigation water requirement for different irrigation system is also smaller; however, this difference is higher for landscape with higher landscape coefficient. GIRR for Honolulu (For $K_L = 0.9$) is 1.9 – 2.2 times higher than that for Houston and 2.4 – 3.2 times higher than that for Tampa Bay for different irrigation systems. The annual average rainfall of Houston and Tampa Bay is more than three times higher than that of Honolulu.

GIRRs vary from month to month according to variation of monthly rainfall (Fig. 2). When the magnitude of rainfall is lower, the GIRR is higher. GIRR is higher for the period of June – September at Honolulu and Houston whereas it is higher for the period of March – June at Tampa Bay.

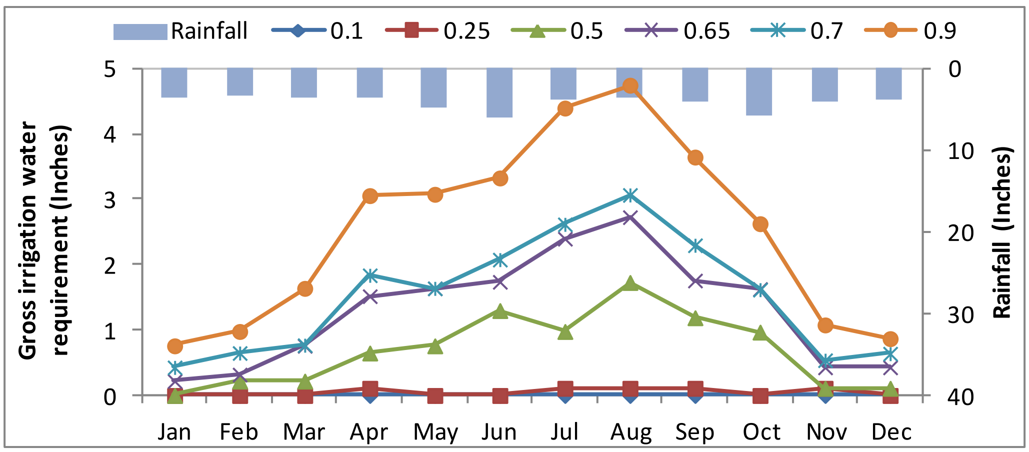


a. Honolulu, Hawaii b. Houston, Texas c. Tampa Bay, Florida

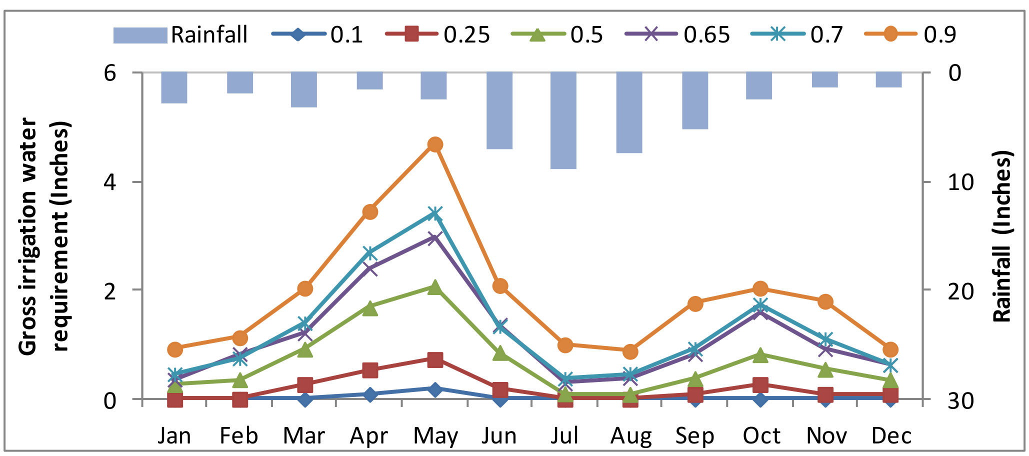
Figure 1. Gross irrigation water requirements for different irrigation systems



a. Honolulu, Hawaii



b. Houston, Texas



c. Tampa Bay, Florida

Figure 2. Monthly variation of irrigation water requirements for different landscape coefficients (Irrigation system: Multiple sprinkler)

Evapotranspiration

In IManSys, daily landscape evapotranspiration is the product of reference potential evapotranspiration and landscape coefficient. The annual average landscape evapotranspiration and reference evapotranspiration for the three locations under different landscape coefficients is shown in Fig. 3. The annual average reference evapotranspiration of Honolulu, Houston and Tampa Bay are 70.9, 60.3 and 44.6 inch, respectively. The landscape evapotranspiration at Tampa Bay is comparatively lower than the other two locations due to its microclimate.

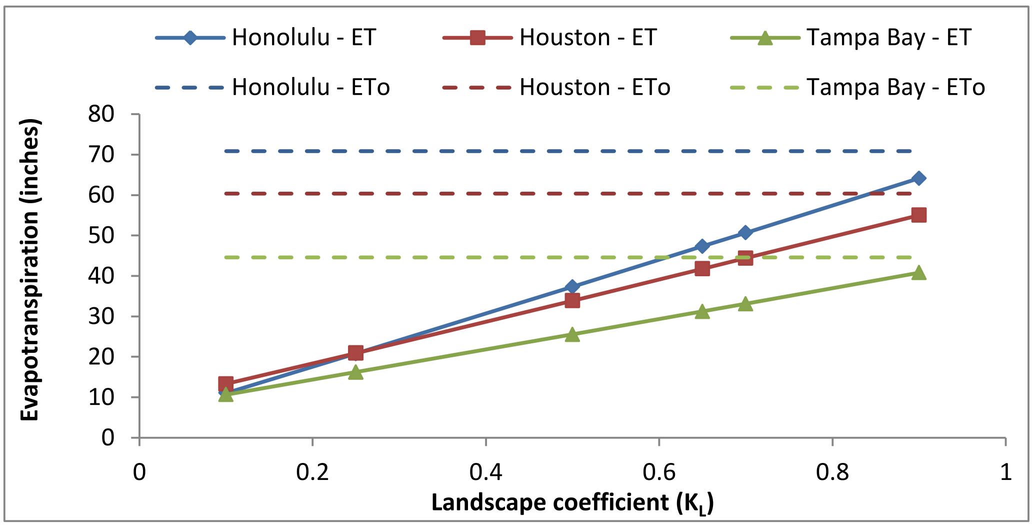
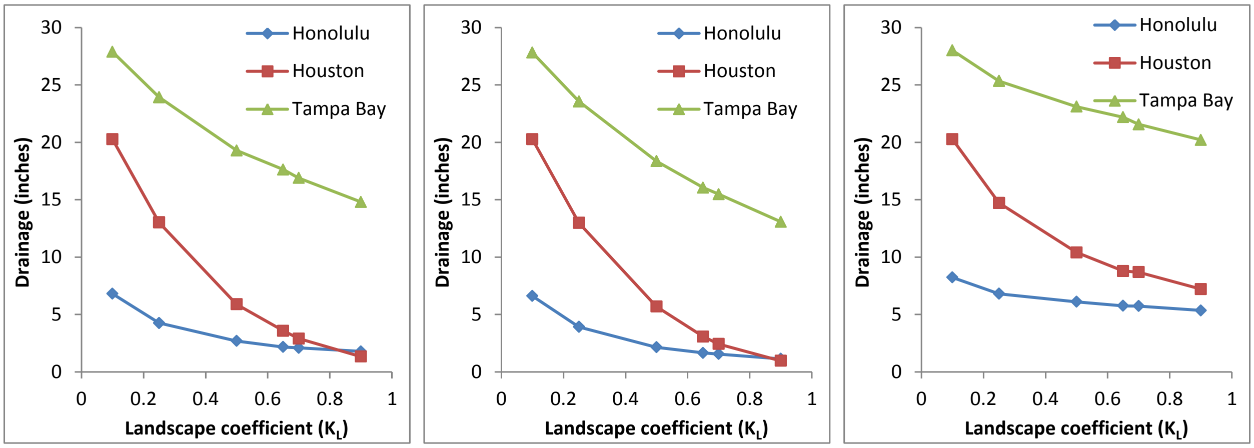


Figure 3. Plant evapotranspiration and potential evapotranspiration for different landscape coefficient

Drainage

Drainage is higher for lower landscape coefficients. Drainage in flood irrigation system is higher than that for the other irrigation systems. In terms of location, the value of drainage for landscape grown in Houston is between those of Honolulu and Tampa Bay for different landscape coefficient.

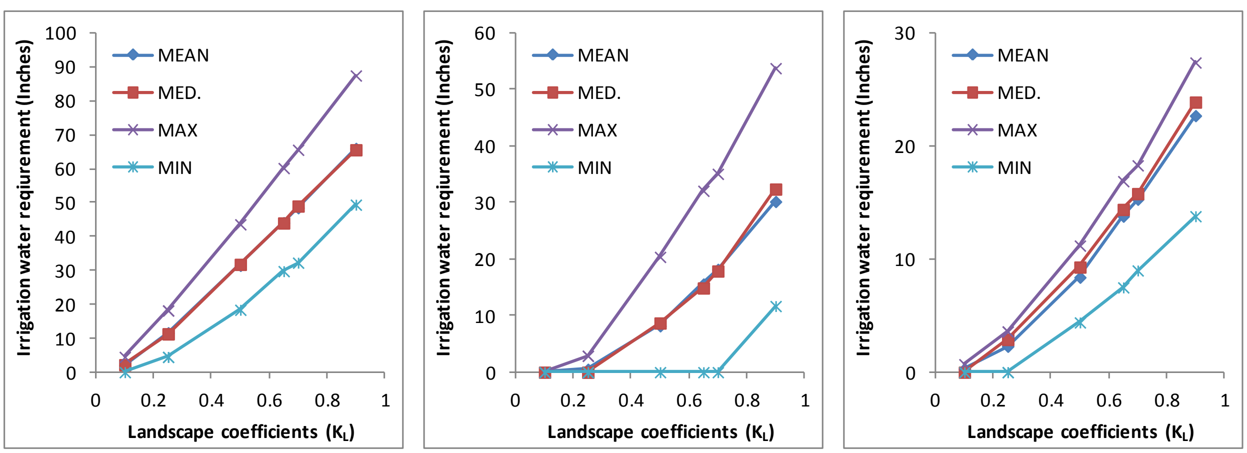


a. Multiple sprinkler   b. Trickle (drip)   c. Flood

Figure 4. Drainage under different irrigation systems

IRRs statistics (Mean, Median, Max. and Min.)

The range of IRRs is higher for higher landscape coefficients. The range of IRR at Tampa Bay is lower than that of the other two locations. This shows lower variation in IRRs at Tampa Bay compare to those at Houston and Honolulu.

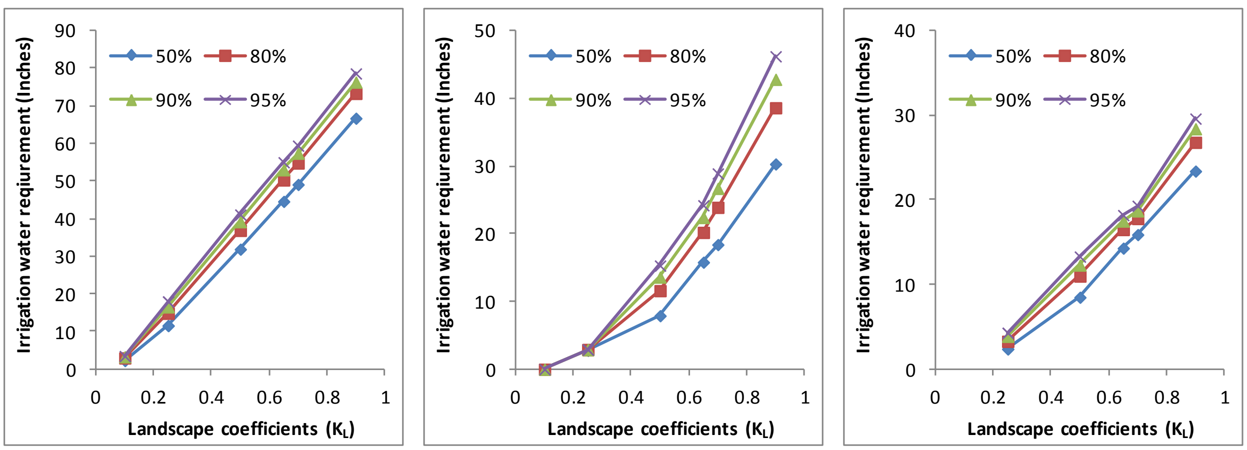


a. Honolulu, Hawaii   b. Houston, Texas   c. Tampa Bay, Florida

Figure 5. Irrigation Requirement Statistics (Irrigation system: Multiple sprinkler)

Irrigation water requirements for different return period

Irrigation requirements for different probability levels are also part of IManSys output. 50% (2 year return period), 80% (5 year return period), 90% (10 year return period) and 95% (20 year return period) probability of IRRS for all locations are shown in Fig. 6. For K_L = 0.9, 5 year return period IRRs are 73.3, 38.6 and 26.8 inches for Honolulu, Houston and Tampa Bay, respectively.



a. Honolulu, Hawaii b. Houston, Texas c. Tampa Bay, Florida

Figure 6. 50%, 80%, 90% and 95% Probability Level of Irrigation Water Requirements (Irrigation system: Multiple sprinkler)

Summary and Conclusions

Irrigation water requirements for several major landscape mixtures at different locations were simulated using IManSys. Weather data, soil properties, and values of landscape coefficients were used as input for IManSys. IRR varies with location, landscape coefficient, and irrigation system. Rainfall and irrigation system efficiency are the major factors impacting IRRs followed by landscape coefficient, irrespective of the location. IManSys proves to be a very useful tool to determine and study IRRs under different conditions.

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COMMERCIAL SUCCESS! Irrigation Inspection Program Produces 19% Water Reduction

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Abstract
In 2008, the City of Allen mandated the Commercial Irrigation Inspection Program which required all Commercial water account holders to have their landscape irrigation system inspected and audited by Certified Landscape Irrigation Auditors once every three years, at their expense. The program was phased in from January 2009 so that by the end of 2012 all commercial accounts had been audited at least once, and 1/3 of the accounts had completed their second inspection. While not all accounts consumption was reduced, in some accounts the consumption was reduced by as much as 60% from before audits. The total water consumed by commercial property accounts was reduced by 19% from comparing 2008 to 2010 consumption reports. Both were normal climatic and water usage years with no drought conditions or water restrictions in place. This presentation will highlight the Allen Land Development Code, where the inspection program is controlled by ordinance; the commercial account holder response to the requirements; the findings of the inspection reports performed by Certified Landscape Irrigation Auditors; and the comparisons of consumption reductions in normal climatic years versus drought conditions.

Introduction

The North Texas area experienced a severe drought in 2005-2006 that sent all the area municipalities and water providers into drought contingency response plans with restrictions for outdoor water use as well as other conservation measures due to critical water supply issues. The City of Allen was in a growth period with residential and commercial developments in their starting phases. The population was around 65,000 this year. City leaders brought forth in their strategic planning session several different water conservation measures and strategies that would help with growth, while still conserving water. In these sessions, the Land Development Code was discussed to include more landscape and irrigation plan requirements, specific plant lists and a requirement for all commercial properties to have an irrigation inspection that includes an audit of the system specified by the guidelines set forth by the Irrigation Association. This inspection requirement was for all new and existing commercial properties to have a recurring inspection every three years and report the findings to the city using forms. (appendix A) Along with these requirements added to the Land Development Code, the City leaders created a Water Conservation division of the Community Services (Public Works) department and position of Water Conservation Manager. The position was open in November of 2007, and Gail Donaldson was hired.

Changes to the Land Development Code were passed through City Council in March of 2008, with full implementation to begin January 1, 2009. This date coincided with the State of Texas mandate of HB 1656 requiring municipalities to implement a landscape and irrigation ordinance requiring all irrigation plans to be reviewed before permit issue, and installation inspections of the systems prior to use. For all commercial irrigation installations, this also includes the inspection requiring an audit. A full audit of the system with one catch-can audit of the largest turfgrass zone (a representative zone) for each controller on the property must be performed at installation, and repeated every three years. The code was amended in March of 2010. The current code is written as follows:

Sec. 7.05.6. Irrigation plan requirements.

1. No person shall install an irrigation system in the city without first having obtained a permit authorizing such installation from the office of the city's department of building and code compliance. In addition to the permit fee established by the city and such other information as may be required by the chief building official, an application installation of an irrigation system must be accompanied by a full set of plans setting forth the design and operation parameters of the irrigation system to be installed, which plans must comply with this section 7.05.6

2. The city shall provide the applicant with an irrigation system plan review checklist, shall evaluate the appropriateness of the irrigation system plan, and shall approve the plans or approve the plans subject to stipulations. Irrigation plans must comply with all State of Texas design and installation requirements including, but not limited to, applicable provisions of V.T.C.A., Administrative Code tit. 30, ch. 344. In addition, the installation and operation of all irrigation systems must comply with the requirements of the city's water conservation ordinance, as amended, as described in the Code of Ordinances section 14-14.1.

3. In addition to the provisions of V.T.C.A., Administrative Code tit. 30, ch. 344, as amended, all new irrigation systems shall meet the following requirements:

   a. The irrigation plan shall be sealed by a licensed irrigator or Texas registered landscape architect.

   b. The system must include an automatic controller and sensors that prevent the operation of irrigation during rainfall or in freezing weather.

c. All non-turf landscape areas shall be designed with drip irrigation and/or pressure compensating tubing (no above-ground spray).

d. All landscaped areas (including areas of turf-grass), regardless of size, located between the sidewalk and curb/pavement edge for any development shall be designed with drip irrigation and/or pressure compensating tubing (no above-ground spray).

e. All drip irrigation and/or pressure compensating tubing shall be designed and installed according to manufacturer's specifications. For subsurface installation, application rate shall not exceed .21 inches per hour.

f. Turfgrass areas utilizing irrigation rotors are to be designed and installed using low-angle nozzles.

g. Irrigation heads shall be installed to provide maximum distribution uniformity. The system shall be designed and installed to provide a distribution uniformity of 63 percent DU_{LQ} or better.

h. The irrigation design shall prevent overspray on impervious surfaces and excessive runoff.

i. Irrigation systems that vary from the standards of this Code and are designed to minimize water usage may be reviewed and approved by the city, provided, however, the design and installation requirements must at all times comply with V.T.C.A., Administrative Code tit. 30, ch. 344, as amended.

4. New irrigation systems for non-single family developments installed in landscaped areas (including turfgrass) that are less than ten feet in width and adjacent to impervious surfaces, or installed in landscape islands with an area of 200 square feet or less shall be designed with drip irrigation and/or pressure compensating tubing (no above-ground spray).

5. All new irrigation systems for single-family homes shall have separate zones for a drip system (drip irrigation and/or pressure compensating tubing) around the foundation.

6. A certified landscape irrigation auditor shall conduct the following required irrigation audits and inspections:

a. Installation audit and inspection: Immediately following installation, an irrigation system audit and inspection shall be required for all new irrigation systems. For new developments, documentation of the audit and inspection shall be submitted to the city prior to issuing a certificate of occupancy. The audit and inspection must include an evaluation of the system distribution uniformity and actual zone precipitation rate. The audit shall be performed according to the latest edition of the Recommended Audit Guidelines, published by the Irrigation Association, 6540 Arlington Boulevard, Falls Church, Virginia 22042-6638. Distribution uniformity shall be measured on the largest turfgrass area zone of the irrigation system. Forms for submission and documentation of audit and inspection information shall be made available by the city.

b.

Recurring inspections: An irrigation system audit and inspection shall be required for all irrigation systems, new and existing, in non-single-family developments and shall be submitted to the city once every three years and shall be conducted in the same manner as set forth in subparagraph a., above, regarding the installation audit and inspection. The city shall establish a timeline and procedures for all developments to submit irrigation system audit and inspection documentation to the city for review. Forms for submission and documentation of inspection information shall be made available by the city.

7.

When existing irrigation systems are expanded by more than 25 percent (25 percent of the land area covered by the system); or more than 25 percent (25 percent of the land area covered by the system) of the irrigation system is replaced, the portion being expanded or replaced shall meet the requirements of this Code.

(Ord. No. 2721-3-08, § 1(Exh. A), 3-25-2008; Ord. No. 2900-3-10, § 10, 3-23-2010)

Implementation

The building and code division of Community Development department are responsible for all irrigation permits, plan review, and irrigation installation inspection. They collect the commercial irrigation audit forms at time of inspection. The hiring and cost of irrigation audits is responsibility of commercial property owners, for the installation and recurring inspections. These forms are sent to Water Conservation division of Community Services (Public Works) and are recorded in a database, and put in a three year rotation schedule for recurring audits. Every three years, the properties will come due for inspection and audit. This inspection is for all non-single family water accounts. These all have separate irrigation water meters (required), and will include multi-family apartments, shopping centers, office buildings, warehouse, storage rental, and Home Owner Association common areas including pools and parks.

For the existing commercial properties, a notice was sent out January 1, 2009 to all property owners of the passing of the ordinance and requirements. In order to implement most effectively, it was decided to split the current properties by installation dates with all the oldest properties to be inspected and audited in 2009. At this time, there were around 600 total existing commercial properties. The first group included 250 properties for inspection, that notice was sent in February to this group with due date of inspection June 30.

Progression

The audit forms began to come in the month of May. Several included detailed reports from the auditors with pictures of what was found at these properties. The auditors worked with the landscape management companies to make repairs necessary for the audit to be completed. Most of these properties had irrigation systems in total disrepair wasting thousands of gallons with each run time. Broken heads, broken pipes, misaligned, sunken and improper nozzles were found on 90% of the properties. This was no surprise, as irrigation systems simply were being overlooked by landscape management companies all this time, as there was never a requirement for these systems to be inspected. Calls from commercial property owners who were due for this inspection began to increase concerned about the expense they had to endure for this new requirement. Several were extremely angry because irrigation repair costs occurred that they had not previously been budgeted for. These costs had to be paid, as they could not comply with the inspection without the repairs. This is the entire intent of this program, as it is not the audit in itself that reduces consumption; it is the repair to the system that reduces. Most commercial companies waste thousands to million gallons of water each year due to use of poorly maintained irrigation systems. In each City, you can drive in the early hours of the morning (between midnight and 6 am) and drive through miles of streets covered with water due to these poorly maintained irrigation systems.

Results

By September, all but 52 of the properties selected had submitted their forms. Reports from auditors indicated that every property they inspected had several repairs needed before they could complete the audit. Less than 1% of the reports indicated distribution uniformity (DU) above .50, and many reported DU less than .18.

Water consumption average (total consumption divided by number of accounts) pre-audit year 2008-09 for commercial accounts was 904,386. At the end of water year 2009-10, total water consumption average was 724,431. Both years, the climate was normal, no water restrictions. The only difference was 1/3 of the commercial irrigation accounts, and the oldest irrigation systems in the City were required to be inspected and audited. Most of these systems needed several repairs and could account for this 19% water reduction.

When looking at individual accounts that were inspected, 85% of these dropped consumption pre and post audit. Around 5% of the accounts increased consumption, the remainder accounts stayed approximately the same. Some accounts decreased consumption by as much as 60% from what was discovered during this inspection process. One small restaurant account in town had seven irrigation zones wired to the controller. As the inspector was going through the zones, he could not determine where zone seven was located. Zone seven had run time programmed similar to all the other zones. While speaking with the manager, the restaurant had expanded its parking lot two years prior. The irrigation inspector discovered zone 7 valve near the expanded parking lot. The valve was still operating every time the controller was set to run. The pipe had been cut and was openly flowing water under the parking lot. The water had caused erosion of the parking lot and the manager admitted having several concrete repairs those two years, but had never discovered they had an irrigation valve flowing water every week. Several reports of water leaks to the main thoroughfare in front of the restaurant had been investigated, as with several pothole repairs to this street over these two years. Since no chlorine was ever detected in the water that came in the street, it was thought by city crews there must be a nearby spring causing the water (a natural occurrence in this area). This find during this inspection not only saved water, but also the repair costs of the parking lot at the restaurant, and the street repairs. Since this repair, the restaurant reduced water consumption 60%, and the city has not had street pothole repair in this area.

After many complaints by small commercial account holders, the ordinance was amended in 2012 to exempt all commercial properties that use less than 20,000 gallons consumption in one year. In 2012, no accounts were exempt. In 2013, five commercial accounts that were due for inspection used less than 20,000 gallons for the year.

After the first year of implementation, the City has received favorable comments from the certified landscape irrigation auditors, and many landscape companies have changed commercial contracts to include monthly irrigation system checks to stay on top of all repairs. Since doing this, those accounts that come due for their inspection do not spend much on repair, and the auditors can perform the audits without wait time for repairs. Many of the managers of these accounts said the water cost savings more than paid for the repairs made, and after seeing this the first year have gone to monthly irrigation inspections (without audit), to insure they are not wasting water through broken irrigation equipment.

As of 2013, 93% of commercial accounts have complied with the requirement and no fines have been issued. Water consumption is still down overall from 2008 consumption rates.

The 2010-11 year, we were beginning a new drought period. The summer of 2011 was highest temperatures, lowest rainfall in the century, however, mandatory water restrictions did not go into effect until August 18. Average water consumption in commercial accounts through August still remained 10% below 2008.

For the 2011-2012 year, we were in Stage two mandatory restrictions of twice per week watering for 6 months, and Stage 3 mandatory restrictions of once per week watering or less for 6 months. The average water consumption was 26% below average consumption of 2008. As of July, 2013 we remain in mandatory water restrictions and consumption averages remain 26% or more below the 2008 figures.

Conclusion

Most commercial properties have landscape maintenance contracts with everything from the large corporate landscape firms, to small one man operations of a truck and lawn mower. Texas requires any person who repairs, sells, consults, designs, install, etc. an irrigation system to be licensed. The license is managed through Texas Commission on Environmental Quality (TCEQ). Because of this license requirement, the smaller commercial properties that use one man operators for landscape maintenance are less likely to employ Texas licensed Irrigator, and thus more likely to not implement monthly irrigation system checks. These are normally the accounts that will benefit from this inspection, yearly inspections would be better.

It is the mandated requirement of this inspection program that continues to reduce demands for our commercial accounts, as without the mandate most of the systems would go neglected and in disrepair wasting much of our water supply. Most of our large commercial accounts have landscape companies that are now performing regular maintenance on the irrigation systems, and have therefore continued to keep their irrigation usage lower. The requirement of irrigation system plan review, and installation inspections have reduced the amount of poor design and installed systems in our new buildings. As of July, 2013, we have over 939 commercial accounts-over 300 new accounts- buildings, shopping centers, HOA's, and multi-family units, and each of these have been installed with more efficient irrigation equipment that help to reduce the overall water usage in their water accounts. By inspecting at installation, most of these new systems are meeting a DU of .63 or greater, improving the water efficiency of irrigation systems. By mandating the inspection be performed by licensed irrigators who are also certified landscape irrigation auditors validates the reports. Those irrigators that have gone through the certification program understand the need for efficiency in an irrigation system, and most value water conservation efforts, and consistently provide trustworthy reports. Many go above the City requirements and offer full water management solutions for these commercial properties with detailed reports for corrections or retrofits to the systems that will save water, with details on the return on investment due to water savings.

The implementation of this program has dropped overall water consumption in our commercial accounts. The total water consumption by this class account is over 500 million gallons a year-even a 10 percent saving is significant enough to implement. The only item that might improve the existing program would be to require the smaller accounts that do not implement irrigation system checks in their maintenance to report annually, instead of every three years. In the continual search for effective water conservation efforts, this is one that does reduce water consumption with very little investment on a municipality. Any municipally could easily add this requirement in their code, and most could use the existing city database software systems to administer the program. The administration time could be incorporated within any customer service representative type position in water services, or building and code and is well worth it when faced with critical water shortages and the need to reduce consumption.

APPENDIX A

CITY OF ALLEN

Irrigation Inspection Form

Please return completed form to address listed on the bottom of page.

Property Information:

Name of Property: ____

Address of Property: ____

Allen, Texas Zip: __________________

Water utility account number: _______________________

Responsible Party (Person with decision making authority regarding property)

Name: ____

Address: ____

City:_________________ State: ____ Zip: ___________

Phone number: _______________________________

Email: ____

Information of person conducting irrigation system inspection:

Name: ____

Address: ____

City: _______________ State: ____ Zip: ________

Phone number: _______________________________ TX LI # _______________

Email: ____

*Certified Irrigation auditor with: ____ Texas A&M ____ Irrigation Association

**** A copy of certification document from either Texas A&M or the Irrigation Association must be on file. If this is your first time to perform an audit, enclose one copy with this form.***
If licensed irrigator is found to be falsifying information, a report will be made to TCEQ.

Irrigation Inspection Form Page 2

Meter Size: _________Meter Number: ________________ Irrigation only? YES NO

Controller Information* (Brand, model):
____

Cross Connection Control device (Brand, type, size): ___________________________

Rain/ Freeze Sensor Brand: ______________________Working? YES NO

TOTAL Number of zones: ______ Irrigation day program (circle all days) M T W Th F S Su

Type of irrigation on controller (all that apply): Spray Rotor Bubblers Drip

System Analysis: All sunken, clogged, misaligned, broken, blocked, or otherwise problem heads have been corrected to maximize efficiency **before** this system analysis was performed. All zones are in most efficient working order and a zone was chosen that most represents the irrigation coverage of 60% of the property turfgrass area. Pressure reading was performed on at least one irrigation head in the zone. An IA method catch-can test was performed to determine PR and DU and results are recorded below. *(Do not audit drip zones)*

Representative Zone information:

Soil Type: _______ Plant Type(s):_________________

Zone # ______ Type of irrigation heads (circle one): Spray Rotor Number of heads:_____

Nozzle type (specialty nozzle?):____

Number of start times for zone: _____ Minutes programmed ________

Actual Pressure reading (on irrigation head) _____ psi

Precipitation Rate (PR): ______ Inches per Hour

Distribution Uniformity (DU_{LQ}): ______

Signature of Certified Irrigation Auditor: _________________________________ (include copy of certificate from either Texas A&M or Irrigation Association if not on file)

Date: __________________

If property has more than one controller, use additional form for each controller. A minimum of one zone per controller must be audited.

Irrigation Consultations for Utility Customers in San Antonio, Texas

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San Antonio Water System

Adolfo Garcia, Senior Conservation Consultant, Licensed Irrigator
San Antonio Water System

Abstract. *The San Antonio Water System's Conservation Department conducts over 2,000 residential and commercial irrigation focused consultations per year. A typical consult starts with a customer request for a conservation consultation. The consult itself consists of water meter reading, review of controller program, system maintenance issues, calculation of gallons per minutes (gpms) per irrigation zone, landscape assessment, and a review of applicable SAWS irrigation design rebates. At the end of the visit a consultation report is left with the customer. The report highlights any found maintenance/repair issues with the recommendation that they be repaired by a license irrigator. In addition the customer is given a recommendation for a more efficient watering schedule. This presentation will focus on the typical findings made by staff and on the documented savings achieved from a consultation which is an average of 25,000 gals/year.*

Keywords. Conservation, irrigation consultation, checkups, irrigation design, utility, rebates, water savings

For more than a century, the Edwards Aquifer has supplied San Antonio, Texas with pure spring water. In the early ’90s, the Federal courts and the Texas Legislature established limits on this primary water supply. After years of discussion and inaction, the community united to address critical water supply issues. So how does a community change from water careless to water careful? Water conservation was immediately identified as one of the ways to address both short- and long-term water needs.

With a service population now reaching approximately 1.6 million people, The San Antonio Water System (SAWS) from the beginning recognized that a significant community ownership of conservation in San Antonio was required for program success.

San Antonio has made significant progress in reducing per capita water use from a high of 225 gallons a day in the mid-1980s to a dry-year low of 136 gallons a day. But challenges still remain particularly outdoor water use.

The Challenge

Landscape water use accounts for 25 percent of annual water use in San Antonio and up to 50 percent in the summer. Customers with automatic irrigation systems are consistently among the highest water users in the SAWS service area. Strategies for reducing outdoor water use must include ongoing and consistent education both for homeowners and professional landscapers.

The Solution

In addition to general public outreach and other water conservation incentives, SAWS offers WaterSaver Irrigation Checkups. This free service assists customers one-on-one with reducing their landscape water use. Most customers find out about this service via the SAWS website and through conservation outreach events.

The primary goal is to:

• Check controller for number of program start times and number of minutes per zone.
• Identify each zone type: Spray, rotor, drip, or bubbler. Is there mixed design?
• Identify plant type by zone, grass vs. flower beds. And by site conditions, shade vs. sun. Check if program is appropriate for the landscape.
• Run each irrigation zone to identify design and maintenance issues with system: broken heads, clogged, not vertical, sunken, blocked, high or low pressure and overspray to impervious areas that contribute to water waste.
• Estimate gallons per minute (gpm) used per zone using water meter reads. This information is then used to estimate the total gallons of water used per cycle, per week and per month.
• Make recommendations on landscape practices and irrigation equipment as necessary to promote efficiencies that result in water savings.
• Give the customer educational material, as well as make them aware of all conservation incentive programs.

At the end of the consultation a copy of a form filled with notes gathered during the checkup is left with the customer. In it are all the findings of the types of issues listed above. The homeowner can make the necessary adjustments and/or repairs themselves or they can use the report to present to a licensed irrigator to do the work.

If design changes are recommended by the conservation consultant the customer is informed of SAWS' Irrigation Design Rebate they can apply for to make their irrigation system more efficient. For example, the customer can convert a popup spray zone to drip for a flower bed, or split a zone to beds and turf. Additionally, the customer is informed of other landscape related rebates SAWS may have available to help them create a more water saving landscape.

The information gathered during the consult is also used to explain the impact of irrigation water use on the customer's water bill giving them a better understanding of the difference between indoor and outdoor consumption. Lastly, if the consultant finds that the homeowner has been overwatering their landscape they are given a recommended watering schedule based on the consultation findings. If they agree with the recommendations and give permission the consultant makes the appropriate scheduling changes to the controller.

Checkup findings in San Antonio, Texas:

• Predominately, homes have drought-tolerant landscapes.
• Controllers are not programmed appropriately for plant material. Typically each zone is programmed with the same run times with little to no consideration given to plant material and site conditions.

• Inappropriately maintained or designed irrigation systems for their landscape.
• Controller intimidation. Typical customer finds controllers too difficult to program thus over programming without intention.
• Customer disconnection to landscape/irrigation system and reliant on landscapers and/or irrigators for programming. Customers are constantly asking conservation consultants to recommend an irrigation professional.
• Awareness of legal responsibility. In San Antonio all irrigation systems must have a working rain sensor. It is sometimes found bypassed or broken. Programs are sometimes found to be in violation of local year round watering rules or of drought restrictions when in effect. Some are unaware that allowing water to run off onto the street due overspray or that failing to repair a controllable leak, such as a broken head, is considered water waste and in violation of local ordinance.

The WaterSaver irrigation checkup usually takes about one hour, but the savings have proven to be substantial. Since 2000, this program has assisted more than 5,000 individual homeowners with irrigation systems saving an average of over 25,000 gallons of water per year. Though labor intensive, this program has proven to be one of SAWS' most effective programs.

Restricting irrigation days: what is the conservation impact?

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Abstract. *The objective of this study was to determine the irrigation savings, if any, of water restrictions in southwest Florida that limited irrigation to once per week as compared to twice per week. This research is based on a previous study of 225 customers in Tampa, Florida and was expanded to include all potable water customers without access to reuse in the City of Tampa and Northwest Hillsborough County, Florida. Monthly water billing records and daily weather data were used to estimate irrigation demands and requirements. Although there is some evidence that water restrictions reduced the irrigation used by high irrigators, the difference in irrigation use of all customers as a whole was not appreciable under one day per week watering restrictions as opposed to two day per week watering restrictions.*

Keywords. Irrigation, Turfgrass, Water restrictions, Water Conservation, Florida

Introduction and Background

A recent study by Ozan and Alsharif (2013) explored the effectiveness of irrigation restrictions on reducing total potable water use. Analysis was based on the monthly combined (indoor and outdoor) water billing records of 225 homes located in three communities within the Tampa, Florida zip code 33647. The communities were identified as having high rates of irrigation violation citations, although homes sampled were randomly selected within the communities and were not necessarily irrigation violators. The periods of analysis were June 2004-May 2006 for once a week watering restrictions and June 2006-May 2008 for twice a week watering restrictions. There was no significant difference in total water use between the two analysis periods. The factor that had the strongest correlation with water use was adjusted rainfall (rainfall minus historic pan evapotranspiration), with a statistically significant ($p<0.05$) r-value of -0.5940 for both once and twice a week restriction periods. The study concluded that the drought conditions caused homeowners to irrigated more despite the more stringent restriction of watering one day per week.

Expanding upon this study, the research presented in this paper aims to evaluate the irrigation habits of all potable water customers without access to reclaimed water in two service areas of Tampa Bay Water, a regional water supply authority: City of Tampa (Tampa) and Northwest Hillsborough County (NWH).

Materials and Methods

Data collection

Tampa Bay Water (TBW) provided monthly billing records for Tampa and NWH. Monthly water billing data was provided for the approximate time period of 1998-2010. Water billing data contained total water use (indoor and outdoor combined) for single-family residential properties. Customers did not have separate irrigation meters or have access to reclaimed water. In addition, TBW provided parcel data that included parcel identification numbers and estimates of the green space area. Because water restrictions are recommended or imposed by local ordinances in addition to the water management district, only one other service area, NWH, had the same water restrictions as Tampa. Therefore, only the approximately 3.5 million monthly records from Tampa and NWH were used in this analysis. The same analyses periods used in Ozan and Alsharif were also used for this study: June 2004-May 2006 for one day per week restrictions (Period 1) and June 2006-May 2008 for two day per week restrictions (Period 2).

Data Analysis

Irrigation Demand

Irrigation was estimated by subtracting the estimated indoor water use from the billing record total water use. The estimated irrigation demand expressed as a depth was obtained by dividing the estimated volumetric outdoor water use by the estimated irrigated area. All outdoor water use was assumed to be due to irrigation and other outdoor uses (e.g., filling swimming pools or washing cars) were ignored. The estimated indoor water use was calculated using an average per capita indoor use of 265 liters/capita/day (70 gallons/capita/day, based on the Mayer et al. 1999 estimate of 69.3 gallons/capita/day), the average household size for each member government service areas (2.38 for Tampa and 2.54 for NWH), as given by the Southwest Florida Water Management District (2011). The estimated irrigated area was the estimated green space area provided in the parcel datasets and was defined as the parcel area minus the sum of the building area and any taxable extra features such as patios. Calculations assumed that the same irrigation rate is applied over the entire landscape.

Irrigation Required

The monthly gross irrigation required (GIR) for each customer was calculated based on site-specific weather and soil conditions and general plant water needs using a daily soil water balance. The daily soil water balance was calculated following Irrigation Association guidelines (2005) and summed to yield monthly irrigation required. The assumed irrigation system efficiency was 80% (based on Davis & Dukes, 2010) and landscape composition was assumed to be 79% turfgrass and 11% ornamental plant beds (based on landscape characteristics of homes in Pinellas County, Florida reported by Haley and Dukes in 2012). Warm season turfgrass crop coefficients varied from 0.45 to 0.75 depending upon the time of year (Jia, Dukes, & Jacobs, 2009). The water requirement for the ornamental plant beds areas was assumed to be zero because typical ornamentals in Florida have been shown to not require irrigation after establishment while maintaining acceptable quality (Moore et al., 2009; Scheiber et al., 2008; Shober et al., 2009; Wiese et al., 2009).

Site-specific weather and soil data were used. Daily evapotranspiration and rainfall data on a 2-km grid were obtained from USGS and SWFWMD, with each grid square referred to as a pixel. A GIS shapefile for the 2-km pixel grid was also provided by SWFWMD. Soil data were obtained from the USDA's Soil Data Mart (Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture, 2013). Soil data was available by county and included soil types and GIS shapefiles of soil polygons.

Calculations were performed using ArcGIS 10 Desktop (Environmental Systems Research Institute, Redlands CA), SAS 9.2 (SAS Institute, Cary NC), and R 2.13.2 (www.r-project.org) to yield a monthly GIR for each customer. Parcel shapefiles were obtained from the Florida Department of Revenue (Florida Department of Revenue, 2011) and used with water customer parcel lists from TBW data to yield a polygon for each identified water customer in the service area. This layer was intersected with the pixel grid to determine every pixel-parcel combination. Following the same procedure as for the pixel-parcel lists, the available water holding capacity (AWHC) for each parcel was assigned. The soil characteristic used was the AWHC in the first 25 cm of soil as a weighted average. The pixel-parcel and soil-parcel lists were combined in SAS to create one list of all pixel-soil combinations for each member-government service area.

All daily weather data were imported into SAS. Since the separate ETo and rainfall data files used the same grid system, the data were combined to yield one dataset of daily weather data (ETo and rainfall) by pixel. The appropriate turfgrass coefficient based on the month was selected during the soil water balance calculations. Daily soil water balances were calculated in R for all pixel-soil combinations using the equations outlined above. Daily GIRs were summed to yield monthly GIRs, which was then exported from R and imported into SAS. For each monthly customer billing record, the monthly GIR that corresponded to the customer's parcel pixel-soil combination was appended to the data row.

Irrigation Ratio

One method of characterizing irrigation is to compare the calculated irrigation applied (demand) to the calculated irrigation required. This ratio, I_{app}/I_{req}, can indicate whether a customer is sufficiently irrigating ($I_{app}/I_{req} = 1$), under-irrigating ($I_{app}/I_{req} < 1$), or over-irrigating ($I_{app}/I_{req} > 1$). This ratio was calculated for each monthly billing record for all customers using the calculated estimated irrigation demand as the irrigation applied and the calculated theoretical GIR as the irrigation required. In addition to using the ratio to identify customers that tend to over- or under-irrigate, the irrigation ratios also provide some control for weather variations. For example, the two days per week watering restrictions time period may have had higher rainfall (and therefore lower evapotranspiration) than the one day per week watering restrictions period, resulting in lower irrigation demand.

Modeling Irrigation Differences

The irrigation use of all customers under the two watering restriction periods was modeled using SAS. The irrigation depths and ratios were not normally distributed and often had a value of zero, so the data was transformed by taking the natural log of the sum of the response variable (i.e. depth or ratio) and one. The data was then fit to a generalized linear mixed model (proc glimmix). The independent variable of interest was the fixed effect of the watering restriction type, either one or two days per week.

Results and Discussion

Mean monthly irrigation during the two watering restriction periods were similar. This confirms the results of Ozan and Alsarif that watering restrictions do not decrease customer's mean monthly irrigation. Mean annual irrigation was 16.1 inches in Period 1 and 16.5 inches in Period 2. Mean monthly irrigation ratios we also similar during the two periods. It was expected that GIR in Period 1 would be higher than the GIR in Period 2 because Period 1 coincided with more severe drought conditions. However, GIR was actually lower during Period 1 (22.0 inches/year) than Period 2 (25.5 inches/year). This may be due to the prevalence of sandy soil with low water holding capacity. Period 2 may have had higher total rainfall, but if the rainfall did not coincide with plant water needs, supplemental irrigation would still be required.

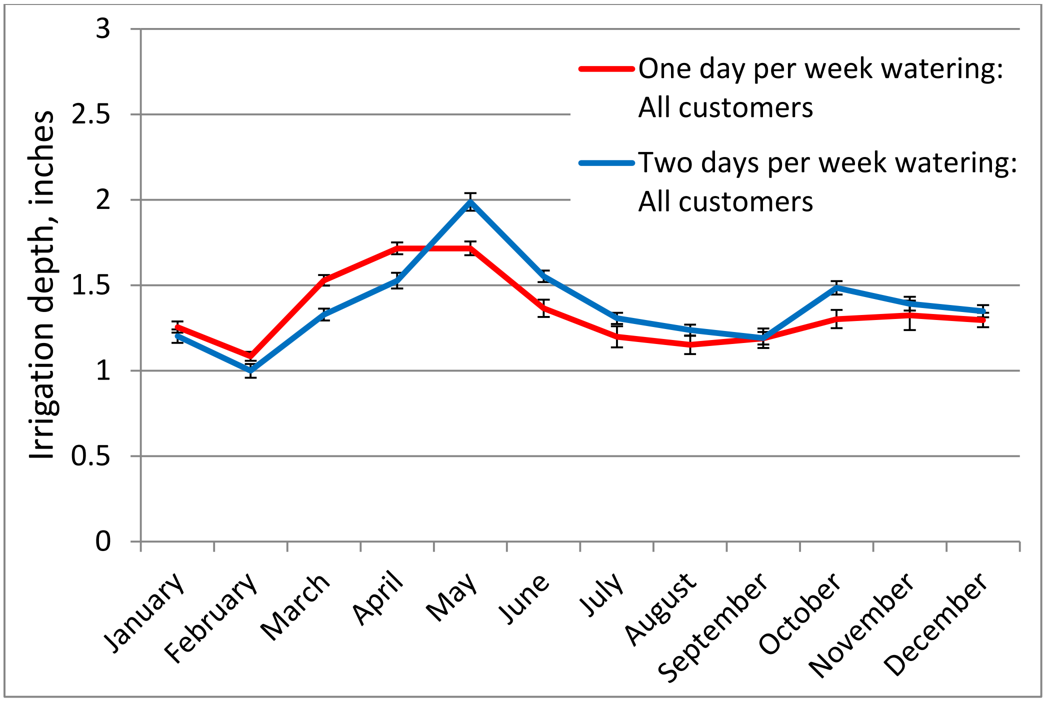

Figure 1. Mean monthly irrigation use of all Tampa and NWH customers during Period 1 (one day per week restrictions) and Period 2 (two day per week restrictions). Error bars indicate 95% confidence interval.

The irrigation habits of customers vary greatly; there is a large portion of customers who only irrigate occasionally and a small portion of customers who irrigate at higher levels. A k-means statistical procedure was used to group irrigators into four categories: occasional, low, medium, and high. Figure 2 illustrates the mean monthly irrigation use of the four groups for Period 1 and 2 combined.

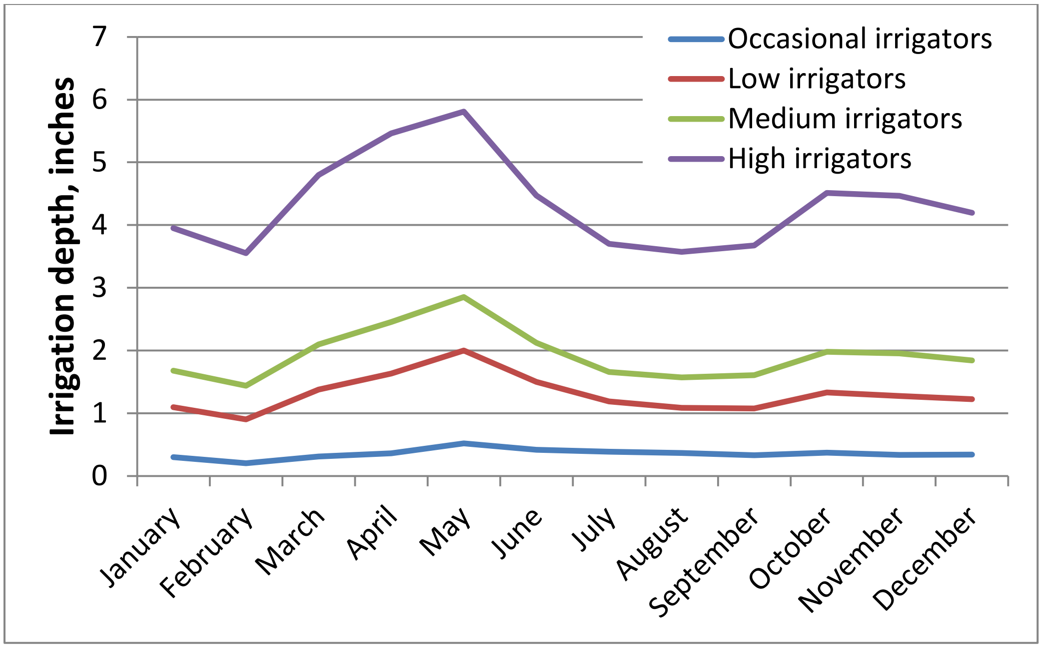

Figure 2. Mean monthly irrigation use of all Tampa and NWH customers by group (occasional, low, medium, and high irrigators).

The response of the occasional and high irrigators to the watering restrictions differed, as shown in Figures 3 and 4. The high irrigator group tended to irrigate more during Period 2 when watering restrictions allowed for two days of irrigation per week. High irrigators used a mean annual amount of 49.4 inches in Period 1 and 55.0 inches in Period 2. Approximately half of the irrigation savings occurred in May and June, when GIR is typically highest. In contrast, the occasional irrigators tended to irrigate more during Period 1, with a mean annual amount of 5.0 inches in Period 1 and 3.7 inches in Period 2. Although high irrigators reduced their mean irrigation by 5.6 inches/year with the more stringent restrictions, aggregate irrigation use of all customers was similar in Periods 1 and 2 because the occasional irrigators increased their mean irrigation by 1.3 inches/year and there was a much higher percentage of occasional irrigators than high irrigators. These results do, however, indicate the success of watering restrictions to limit the irrigation use of high irrigators who often over-water their landscapes.

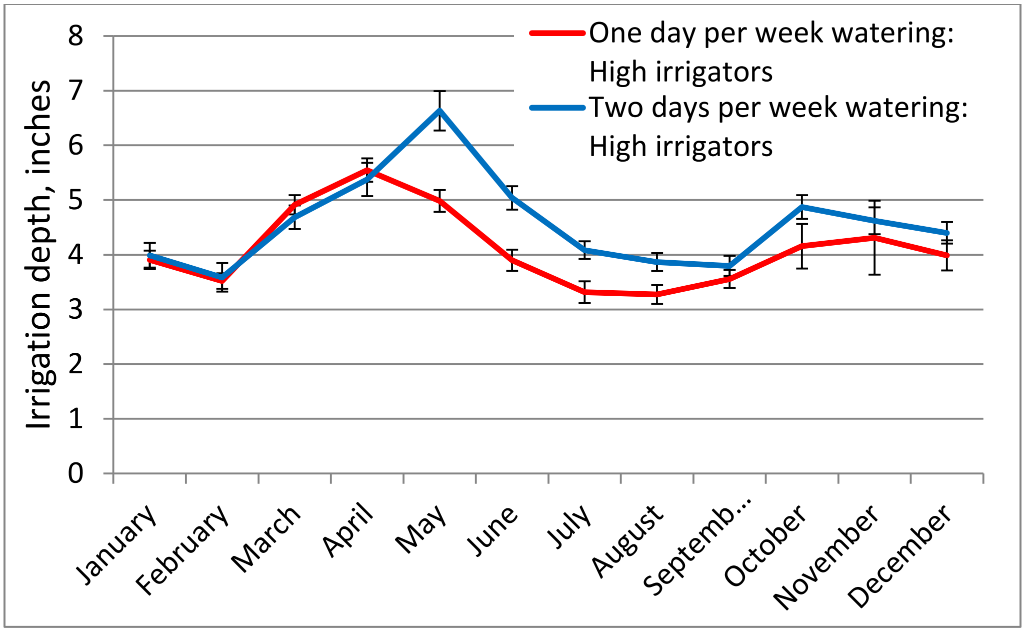

Figure 3. Mean monthly irrigation use of high irrigators in Tampa and NWH during Period 1 (one day per week restrictions) and Period 2 (two day per week restrictions). Error bars indicate 95% confidence interval.

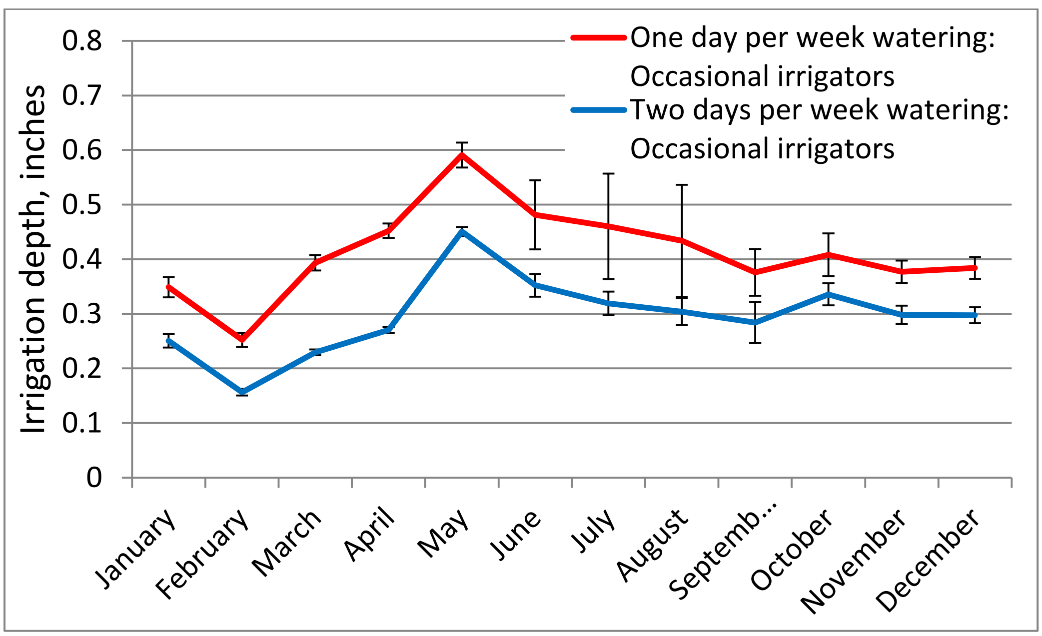

Figure 4. Mean monthly irrigation use of occasional irrigators in Tampa and NWH during Period 1 (one day per week restrictions) and Period 2 (two day per week restrictions). Error bars indicate 95% confidence interval.

Conclusions

The relative ineffectiveness of watering restrictions to reduce irrigation in Tampa and Northwest Hillsborough County, Florida may be in conflict with the beliefs and practices of many utilities that rely on irrigation restrictions to reduce utility-wide annual irrigation demand. Although there is some evidence that water restrictions reduced the irrigation used by high irrigators, the difference in irrigation use of all customers as a whole was not appreciable under one day per week watering restrictions as opposed to two day per week watering restrictions.

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Targeting Excessive Irrigation Customers to Maximize the Benefits of Smart Controllers

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Abstract. *Studies have shown minimal impact by smart irrigation controllers when installed without targeting over-irrigators. The objective of this research was to evaluate different methodologies for identifying residential over-irrigators. Two independent smart controller studies were conducted by utilities in Hillsborough (HCWRS) and Orange (OCU) Counties, Fla. In HCWRS, the cooperators qualified when irrigation was in the top 50th percentile of potable water users in the county and located in three densely-populated cities. In OCU, 112 cooperators across seven locations received smart controllers when frequently irrigating more than 1.5 times the gross irrigation requirement (GIR). Actual ratios of historical average irrigation to the GIR ranged from 1.45-2.37 in HCWRS and 6.04-8.33 in OCU. As a result, cooperators in OCU showed significant reductions in irrigation with a return on investment of 4-14 months compared to HCWRS with a payback period of 6.5-13.4 years. Using the GIR as a benchmark proved to be a better method than using utility-wide median irrigation application to target homeowners for smart controllers to ensure irrigation reductions.*

Keywords. GIR, ratios, residential irrigation, smart controllers

Introduction

Research studies have shown that smart controllers are most effective at increasing efficient irrigation practices when implemented by historical over-irrigators. However, most government or utility programs that focus on water conservation, such as rebate or trade-in programs, make smart controllers available to everyone indiscriminately. The objective of this work was to evaluate methodologies for identifying single family home utility customers capable of achieving significant benefits from implementing smart controllers.

Materials and Methods

Two independent irrigation studies were implemented in Hillsborough (HCWRS; Feb. 2009 to Jan. 2011) and Orange (OCU; Nov. 2011 to Oct. 2012) Counties, Fla. to determine the water conservation potential of smart controllers.

In HCWRS, 36 cooperators voluntarily participated in the study if they resided in one of the three selected communities, were in the top 50th percentile of county water users determined by Romero and Dukes (2010), and had irrigation systems with adequate performance. Twenty-one cooperators were outfitted with Toro Intelli-Sense™ TIS-612 (Riverside, CA) ET controllers (ET+Edu) that used WeatherTRAK ET Everywhere™ signal service (Hydropoint DataSystems, Inc., Petaluma, CA). The remaining 15 cooperators maintained their current irrigation practices (comparison). The ET controllers were programmed by UF-IFAS using default values except customized application rates by zone and irrigation system efficiencies.

In OCU, historical irrigation was determined from monthly billing records over a seven-year period by assuming indoor water use of 67 gpd and 2.2 persons per account. Estimated irrigation was evaluated against the GIR, thus creating monthly ratios (estimated irrigation/GIR). Volunteers were eligible when ratios were greater than 1.5 for at least 3 months per year for three consecutive years. There were 139 participants located across seven locations where each location had five treatments replicated four times except for one location where one treatment had three replications (19 cooperators). Two treatments consisted of Rain Bird ESP-SMT ET controllers and two treatments consisted of Baseline WaterTec S100 SMSs. Two treatments, one for each technology, were installed using methods determined solely by the installing contractor without UF-IFAS intervention. The remaining two technology treatments included UF-IFAS training for the contractor prior to installations, site-specific programming of the smart technology, and cooperator education. The final treatment was a comparison treatment that did not receive intervention.

Historical billing records for HCWRS (7 years) and OCU (5 years) were provided to estimate historical irrigation from combined indoor and outdoor water use by subtracting estimated indoor water use. In both studies, the average monthly indoor water use estimated for each participant during the study period was applied to the corresponding historical month.

The GIR was calculated by multiplying the net irrigation water requirement (IWR_{net}) by a scheduling multiplier (SM). The IWR_{net} is defined as the amount of irrigation required to increase soil water storage to field capacity (FC) (IA 2005). The IWR_{net} was determined from mass conservation of soil water content (IA 2005):

$$IWR_{net} = PWR - R_e \quad (1)$$

The PWR is the plant water requirement (in.) and R_e is effective rainfall (in.). The IWR_{net} was accumulated daily, but was applied only on days when the soil water level fell below management allowable depletion (MAD), calculated as 50% of the difference between FC and permanent wilting point (PWP) (IA 2005).

The PWR equals the plant-specific evapotranspiration (ET_C) using the following equation (Allen et al. 1998):

$$ET_C = K_C * ET_O \quad (2)$$

The ET_O was calculated by the American Society of Civil Engineers – Environmental and Water Resources Institute (ASCE-EWRI) standardized ET equation (ASCE-EWRI 2005). The K_C values were updated monthly for turfgrass ranging from 0.45 (December-February) to 0.90 (May) (Jia et al. 2009).

Effective rainfall was the portion of total daily rainfall that filled the soil storage capacity after PWR was taken into account. Rainfall that exceeded the soil storage capacity was lost due to surface runoff or deep percolation.

A scheduling multiplier (SM) based on the average uniformity of the irrigation system was used to convert IWR_{net} to GIR. The SM was determined from the DU_{lq} using the following equation (IA 2013):

$$SM = 100/(38.6+61.4*DU_{lq}) \quad (3)$$

The calculated DU_{lq} values for each participant were used for the HCWRS study whereas an estimated average of 0.674 was used for the participants in OCU.

Statistical analyses were performed using Statistical Analytical Systems (SAS) software (Cary, NC). The ratios were analyzed using the glimmix procedure and comparisons were made using the least mean square differences by treatment. Significance was determined at a 95% confidence level.

Results and Discussion

The ratios calculated for HCWRS, ranging from 1.45 to 2.37, were much lower than the ratios calculated for OCU, ranging from 6.04 to 8.33, due to higher amounts of irrigation applied in OCU compared to HCWRS. Though the 95% confidence intervals for the ratios in HCWRS were above 1, the cooperators were not good candidates for smart controllers.

To determine the return on investment for a smart controller, it was assumed that the purchase and installation of a SMS or ET controller was $400 and $600, respectively, based on communications with contractors across Florida. Additionally, the landscape area was assumed as 5,000 ft^2 for this analysis. In HCWRS, an annual return of

$45.13, $60.39, and $94.42 in Riverview, Valrico, and Apollo Beach, respectively, was observed from implementing an ET controller. Based on these totals, it would take 6.5 to 13.4 years to profit from the ET controller. Annual savings were much higher in OCU than the HCWRS study, ranging from $549.22 to $1,572.78. This resulted in more preferable rates of return with payback periods ranging from 4 months to 14 months.

Conclusion

Partitioning utility customers based on the median estimated irrigation did not produce over-irrigators since most of the excessive irrigation occurs by customers in the 95th percentile. Ultimately, the gross irrigation requirement combined with an irrigation evaluation proved to be a better method than using utility-wide median irrigation application to target homeowners as candidates when focused on reducing the overall potable water demand.

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Water Restrictions Can be Positive –
An Educational Approach to a Mandate

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Abstract: *Fort Collins Utilities implemented an educational approach to engage its community to support and comply with water restrictions. This approach focused on a campaign that used steps to create participation without heavy-handed enforcement. The steps began with* ***awareness****, created through advertising campaigns.* ***Knowledge****, spells out the ordinance and who is affected, is followed by an* ***attitude*** *step that creates a mentality of "I should do my part". Fort Collins Utilities offers programs to give customers the* ***skills*** *to achieve conservation which gets them to the final step of* ***participation*** *or complying with the water restrictions. A similar approach was used the last time Fort Collins experienced water restrictions. Since then, the community has demonstrated a 25 percent reduction in water use.*

Keywords: Water restrictions, mandate, education, water conservation, Fort Collins

Water Restrictions Can be Positive –
An Educational Approach to a Mandate

How do you get 140,000 people to change their long term water use habits? Start with implementing water restrictions in the spring and continue to educate your public about water conservation. An educational approach to a mandate is not new but using community-based social science concepts, and engaging staff with a foundation in environmental education, may be. Our approach was to educate our public, starting internally with utilities staff, with hands-on and varying learning-style approaches before and during water restrictions. We created a recognition program to showcase businesses and community members that exemplified the behavior change we required. We used community allies such as the school district and university to help us communicate. During the presentation, data and results will demonstrate how an educational approach is effective and long-lasting.

Fort Collins, Colorado is located 60 miles north of Denver and nestled in the Rocky Mountain foothills. This mid-sized city has been showered with awards and recognition, such 2012 accolades for "Top Downtown in the Country," *Livability.com*- Nov 2012 and "Platinum Bicycle Friendly Community," *League of American Bicyclists* - May 2013. Fort Collins Utilities is a municipal utility that provides water to about half of the Fort Collins residents and businesses (35,000 customers) in addition to electric, waste water and stormwater services.

Fort Collins Utilities receives raw surface water from two main sources, the Cache la Poudre River and Horsetooth Reservoir. On average, each source provides about half of the supplies used to meet Utilities' customer water demands. Utilities were uncertain how much water would be available in 2013. The 2012 High Park fires in the Poudre Canyon limited the amount of Poudre River water available to treat due to poor water quality from rainfall over the burn area and fluctuations in the river flow. In addition, persistent drought conditions continued to impact the amount of water supply available.

These conditions lead to a decision to enforce water restrictions, starting April 1. Fort Collins Utilities used an educational approach to engage its community to comply with water restrictions. A similar approach was initiated in 2002-2003, the last time the city experienced water restrictions. Since then, water conservation efforts have demonstrated a 25 percent reduction in water use. Starting with awareness through participation, our approach is outlined below.

Awareness

Utilities worked with Colorado State University professors to create effective messages around our mass media communication campaign to make our community aware that water restrictions were in effect. The outreach materials were designed in a way that could be used beyond the need for mandatory restrictions.

Knowledge

Knowledge was built through a community outreach campaign. Businesses most affected by water restrictions and various audiences were identified. A speaker's bureau was created to reach out to all City employees, the community and each of the 10 highly impacted sectors, (1,400 total people). Additional outreach efforts were made to reach the low-income, and Hispanic population, senior citizens and schools. All of these efforts built on the existing water conservation programs.

Water restriction programs were developed to assist homeowners in their efforts to comply with the restrictions. A contractor open house was used as a forum to reach out to local landscape and irrigation contractors and explain the ordinance. Permits were available for those with hardships or large properties, benefiting a total of 171 customers at no cost to the public.

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Attitude

Building awareness and a strong knowledge base allowed our community to form its attitude that "Water is important, I should do my part." We did have some customers call in with a "What are you going to do about it?" attitude. This was approached in a way that educated the caller about the drought, effects from the recent fires and the ultimate decision to restrict water use. With this attitude of valuing water, skills were made available and compliance with restrictions was easily achieved. We built an attitude to conserve water by creating a new recognition program.

Skills

Even when a citizen is aware of water restrictions, has an understanding of why we have them and shares the attitude that restricting water use is the right thing to do, he may not know what to do. This is where Fort Collins Utilities built in the skill to understand what can be done. For 13 years, the Fort Collins Utilities has administered a free sprinkler audit program for customers and neighboring water districts. The audit program educates customers on landscape water needs and general skills to maintain and operate a sprinkler system. A program analysis shows that customers that participate in a sprinkler audit average 20 percent less water on their landscapes. Programs offered during restrictions include:

- Free sprinkler audits
- Free controller assistance (programming controllers for restrictions)
- Extensive programs on xeriscaping and sprinkler workshops

Participation

Ultimately, by using these steps toward behavior change, our water restrictions campaign was successful. Our community was on board. They complied, and when they didn't – we gave them the tools to comply. We had support from all community sectors and widespread understanding for the decisions. This ultimately led to "participation" or willingness to comply with water restrictions.

Conclusion

Fort Collins Utilities chose an educational approach to enforce a mandate during a time of short term restrictions so that long term values of water are imbedded in our community. We created a positive campaign that gave the tools to the community to react and comply with water restrictions. We offered knowledge internally and externally through a speaker's bureau and an extensive advertising campaign. We identified those businesses and customers who were actively participating and making great efforts in conservation, and rewarded them. These steps led to successful acceptance of mandated water restrictions.

Soil Moisture Sensor Performance in Turfgrass Plots Irrigated with Reclaimed Water

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Abstract. *The use of soil moisture sensor systems (SMSs) in turfgrass plots irrigated with reclaimed water (RW) has not been studied. RW can contain more salts than potable water; which might affect SMS readings. The objectives of this experiment were to: a) analyze the behavior consistency of SMS replicates within a brand, b) quantify the potential irrigation water savings of 4 SMS brands, and c) compare the different brands against each other. The experimental area was located in Gainesville, Florida. Four quarter-circle pop-up sprinklers irrigated 60 plots (3.66 x 3.66 m each) covered with St. Augustinegrass (Stenotaphrum secundatum [Walt.] Kuntze). Treatments included a time-based without-sensor (WOS) and four SMS-based treatments; brands: Aquaspy, Baseline, Dynamax, and Acclima (AQU, BAS, DYN, and ACL, respectively). Replicates from AQU were the only ones with significant different behavior within a brand. The irrigation water savings compared to WOS averaged 45, 61, 61, and 68% for AQU, BAS, DYN, and ACL respectively.All SMSs tested responded properly to soil water conditions and might be a useful tool for conserving water on turf irrigated with reclaimed wastewater.*

Keywords. Reclaimed water, soil moisture sensor, turfgrass quality, water savings.

Introduction

The dry and warm weather during spring and fall in Florida, and the sporadic large rain events in the summer, coupled with the low water holding capacity of its prevalent sandy soils, make irrigation indispensable for high quality landscapes desired by homeowners (Baum et al., 2005; NOAA, 2003). In Florida, turfgrass represents the largest cultivated crop, which is irrigated with reclaimed water (RW) in several municipalities.

Of the commercially available soil moisture sensor systems (SMSs) for residential use, the most common type is known as an “add-on” device. These SMSs consist of a probe to be inserted in the root zone of the turf area and a controller to be connected to the time clock, or timer, of an automated irrigation system. On the controller, the user can set a soil water content threshold. Then, depending on the soil water content at the programmed start time, the SMS will allow or bypass that scheduled irrigation cycle, depending if it is drier or wetter than the threshold, respectively.

Under turfgrass plots conditions, irrigation systems receiving feedback from SMSs have saved potable water compared to typical time-based irrigation systems (Cardenas-Lailhacar et al., 2008 and 2010; McCready et al., 2009; Grabow et al., 2013). This technology has also demonstrated potable water savings in homeowner settings (Grabow et al., 2010; Haley and Dukes, 2011). In these studies, the reported overall turfgrass quality was above minimum acceptable, regardless of the water savings.

The use of SMSs in turfgrass plots irrigated with RW has not been reported. Most of the SMSs marketed for landscape irrigation respond to electromagnetic properties of the soil, more specifically, to the dielectric permittivity. Compared to potable water, RW can contain more salts, which may alter the dielectric permittivity of the soil and, hence, affect the readings of SMSs when measuring the soil water content.

This research was carried out on turfgrass plots irrigated with RW. The objectives were to: a) analyze the behavior consistency of SMS replicates within a brand, b) quantify the potential irrigation water savings of 4 SMS brands, and c) compare the different brands against each other.

Materials and Methods

The experiment was installed at the Agricultural and Biological Department facilities, University of Florida, Gainesville, Florida; on Arredondo fine sand (loamy, siliceous, semiactive, hyperthermic Grossarenic Paleudults) (USDA, 2013). Sixty plots were covered with St. Augustinegrass (*Stenotaphrum secundatum* [Walt.] Kuntze), cultivar Floratam. Each plot was 3.66 m X 3.66 m and sprinkler irrigated by four quarter-circle, 15 cm pop-up spray heads (Rain Bird sprinklers 1800 series, 12Q nozzles; Rain Bird International, Inc., Glendora, Calif.). The RW used for irrigation came from the University of Florida Water Reclamation Facility; and had an average electrical conductivity (a measurement of water salinity) of 0.75 dS/m, which is classified as medium-high according to the U.S. Salinity Laboratory (1969).

Four commercially available SMSs were selected for evaluation: Acclima Digital TDT (Acclima Inc., Meridian, ID), Aquaspy (AquaSpy Inc., CA), Baseline biSensor (Baseline Inc., ID), and Dynamax SM200 (Dynamax Inc., TX), coded as ACL. AQU, BAS, and DYN, respectively (Table

1). Each SMS probe was positioned in the center of a different plot, with the midpoint of their sensing portion buried at a depth of 8 cm, in the top 7 – 10 cm of the soil, where most of the roots were present.

The plots containing a sensor for irrigation control were saturated and allowed to drain for 24 hours, to reach field capacity. Then, SMS readings were taken and the thresholds were set individually on each controller. The following procedure was conducted to determine the individual set points (all units in percentage of volumetric water content, except for MAD):

$$FC - PWP = AW \quad (1)$$

$$\text{Threshold Set Point} = [(1\text{-}MAD) \times AW] + PWP \quad (2)$$

where: FC = Field capacity, PWP = permanent wilting point (in this case, 4% was considered to be the PWP), AW = available water, and MAD = maximum allowable depletion (in this case, a factor of 0.3–equivalent to 30%–was considered).

Treatments

Two basic types of treatments were defined: SMS-based treatments, and time-based treatments (Table 1). Within the time-based treatments, and to simulate requirements imposed on homeowners by Florida Statutes (Chapter 373.62), two time-based treatments were connected to a same rain sensor: with-rain-sensor (WRS) and deficit-with-rain-sensor (DWRS). The rain sensor (Mini-click II, Hunter Industries, Inc., San Marcos, CA) was set at a 6 mm rainfall threshold. A without-sensor treatment (WOS) was also included, in order to simulate common homeowner irrigation systems with an absent or non-functional rain sensor or SMS; and was the main comparison treatment. The SMS-based treatments were replicated three times. Every treatment /replicate were controlling the irrigation of four plots each, in a completely randomized design.

All irrigation cycles were programmed on two ESP-6Si, and three ESP-4Si timers (Rain Bird International, Inc., Glendora, CA), and set to start at 0600 h, with the purpose of diminishing wind drift and decreasing evaporation. Treatments were set to run 3 days per week (to mimic homes—as part of a companion study—using RW as its irrigation source in Pinellas Co. which are allowed to irrigate 3 days per week [PCU, 2010]). All treatments were programmed to run for the same amount of time; except for treatment DWRS which was programmed to run for just 60% of this schedule. Therefore, differences in water application among treatments was the result of sensors bypassing scheduled irrigation cycles. All the runtimes were adjusted monthly, to replace 100% of the historical ET-based irrigation schedule recommended for the Gainesville area by Dukes and Haman (2002).

Data collection

Date, time, and amount of irrigation applied to each plot was continually recorded through pulse-type positive displacement flowmeters (PSMT 20mm x 190mm, Amco Water Metering Systems, Inc., Ocala, FL) that were connected to nine AM16/32 multiplexers (Campbell Scientific, Logan, UT), which were hooked up to a CR 10X model datalogger (Campbell Scientific, Logan, UT).

Weather data were collected by an automated weather station (Campbell Scientific, Logan, UT), located within 1 m of the experimental site. Measurements made every 15 minutes included minimum and maximum air temperatures, relative humidity, wind speed and direction, and solar radiation. Rainfall was recorded continuously by a tipping bucket rain gauge on the weather station and a nearby manual rain gauge.

Turfgrass quality was visually assessed and rated using a scale of 1 to 9 where 1 represents brown, dormant turf, and 9 represents the best quality (Shearman and Morris, 1998). A rating of 5 was considered to be the minimum acceptable turf quality for a homeowner.

Data presented in this publication represent the first season of an ongoing experiment, and were obtained from 17 August through 23 November 2010. Data analysis was performed using the general linear model (GLM) function of the Statistical Analysis System software (SAS, 2008). Analysis of variance was used to determine treatment differences and Duncan's Multiple Range Test was used to identify mean differences. Differences were considered significant at a confidence level of 95% or higher ($p \leq 0.05$).

Results and Discussion

Rainfall

During the research time-frame, two different and defined rainfall conditions occurred (Figure 1). From 17 August to 29 September (44 days) the number, frequency, and depth of rainfall events were considered adequate for irrigation purposes and, compared to historical records, estimated as a normal to wet weather condition. Conversely, from 30 September until the end of this experiment on 23 November (55 days) only 10 mm of rain fell (compared to 110 mm of a normal year), including more than a month with no rain at all (Figure 1). Therefore, this second period was considered very dry.

Turfgrass

During the normal to wet weather conditions, no significant differences in turfgrass qualities were found between the treatments, which were all rated as ≥ 6 (data not shown). During the dry period, the St. Augustinegrass suffered an unrelenting quality decline. Turf specialists diagnosed a massive infestation of take-all root rot (*Gaeumannomyces graminis var. graminis*)—which had no chemical control—possibly due to the weather conditions. The turfgrass quality was not considered for analysis during this dry period, because was not a result of the different irrigation treatments.

Irrigation bypass proportion

Every treatment was programmed to run a total of 42 irrigation cycles during this study. Table 2 shows the number and proportion of the scheduled irrigation cycles (SICs) that were bypassed by the different treatments, as well as the average proportion bypassed by the different SMS brands and replications. The time-based treatment without sensor feedback (WOS) was programmed to run independently of the weather and/or soil moisture conditions, so no (0%) SIC was bypassed. The two time-based treatments that were receiving feedback from the same rain sensor (WRS and DWRS) bypassed 21% of the SICs. Conversely, 55% of the SICs were bypassed on average by the SMS-based treatments.

Regarding the different SMS brands, on average, AQU bypassed the least amount of SICs, with an average of 44%, followed by DYN and BAS, with 56% and 58%, respectively. Brand ACL bypassed the greatest amount of SICs, with an average of 63%. The majority of the irrigation cycles bypassed by the SMS-based treatments occurred during the rainy period; verifying that the tested SMSs worked properly under reclaimed wastewater conditions, with variable results. In addition, all SMS-replicates bypassed more SICs compared to the treatments with rain sensor feedback; which is consistent with previous findings (Cardenas-Lailhacar et al., 2008 and 2010).

Irrigation application

The cumulative irrigation through time allowed by the time-based treatments is shown in Figure 2, and by the SMS-based treatments is shown in Figures 3 through 6. All of these treatments are compared to the reference treatment (WOS), which applied a total of 461 mm.

Figure 2 shows that, as designed, treatment WOS applied a cumulative irrigation of 461 mm. The two treatments connected to the same rain sensor, WRS and DWRS, applied 340 and 223 mm, respectively; representing 26 and 52% of water savings compared to WOS, respectively. These water savings were achieved as a result of the bypassed irrigation cycles only during the rainy period (from the beginning of the experiment until 29 September). After 29 September no scheduled irrigation cycle was bypassed by the rain sensor due to the absence of rain events close or greater than 6 mm (threshold set on the rain sensor). Treatment DWRS applied 66% of the total water applied by WRS, which was close to the target of 60%. These results are concordant with those achieved by rain sensor treatments, in the same experimental field, in previous studies (Cardenas-Lailhacar et al., 2008 and 2010).

From Figures 3 through 6, it can be seen that all SMS replicates and brands applied less water than the comparison treatment (WOS), as a consequence of the SMSs bypassing scheduled irrigation cycles (Table 2). The different replicates from brands ACL, BAS and DYN behaved very similarly through time, resulting in comparable amounts of cumulative irrigation water applied by the end of the experimental period. The range of water savings between the replicates fluctuated by 8, 7, and 10 percentage points for brands ACL, BAS, and DYN, respectively; which make them very consistent and reliable. On the other hand, brand AQU resulted in a wider range of cumulative water applied between replicates, with a variation of 26 percentage points.

The brand that, on average, allowed the least irrigation was ACL, followed by BAS and DYN (Figure 7), with totals of cumulative irrigation of 147, 178, and 181 mm, respectively. The AQU system allowed more irrigation than any other brand, with an average of 255 mm; which resulted in a significant difference ($P<0.05$) with ACL. If AQU is not considered for this analysis, ACL, BAS, and DYN were not significantly different (data not shown). The irrigation water savings compared to WOS averaged 45, 61, 61, and 68% for AQU, BAS, DYN, and ACL respectively. The average water saved by all SMS-based treatments compared to WOS was 59%; which is concordant with previous results (Cardenas-Lailhacar et al., 2008 and 2010).

Conclusions

Even when RW with an average salinity of 0.75 dS/m was used as the irrigation source, results of the different treatments and brands were consistent with those of the previous studies, when potable water was used to irrigate the turf. The majority of the irrigation cycles bypassed by the SMS-based treatments occurred during the rainy period. Cumulative water savings were lower than those obtained in normal to wet weather conditions, but higher than those previously reported during dry weather conditions. These results verified that the SMSs tested responded properly to differing agro-climatic conditions, and that SMSs might be a useful tool for conserving water on turf irrigated with RW.

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Acknowledgements

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Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the University of Florida and does not imply approval of a product or exclusion of others that may be suitable.

Table1. Treatment codes and descriptions.

Treatment Codes	Treatment Description or Soil Moisture Sensor Brand	Replicates codes	Set point
Time-Based			
WOS	Without sensor		N/A
WRS	With rain sensor		6 mm
DWRS	Deficit with rain sensor		6 mm
SMS-Based			
ACL	Acclima	1-ACL, 2-ACL, 3-ACL	
AQU	Aquaspy	1-AQU, 2-AQU, 3-AQU	
BAS	Baseline	1-BAS, 2-BAS, 3-BAS	
DYN	Dynamax	1-DYN, 2-DYN, 3-DYN	

Table 2. Scheduled irrigation cycles bypassed by treatments, from a total of 42 possible.

Treatments and Replicates	Total Bypassed (#)	Total Bypassed (%)	Average Bypassed (%)
Time-based			
WOS	0	0	
WRS	9	21	
DWRS	9	21	
SMS-based			
1-ACL	29	69	
2-ACL	25	60	63
7-ACL	26	62	
1-AQU	19	45	
2-AQU	23	55	44
7-AQU	13	31	
1-BAS	27	64	
2-BAS	23	55	58
7-BAS	23	55	
1-DYN	23	55	
2-DYN	26	62	56
7-DYN	22	52	
Average of SMS[z]-based		55	

[z]SMS = soil moisture sensor system.

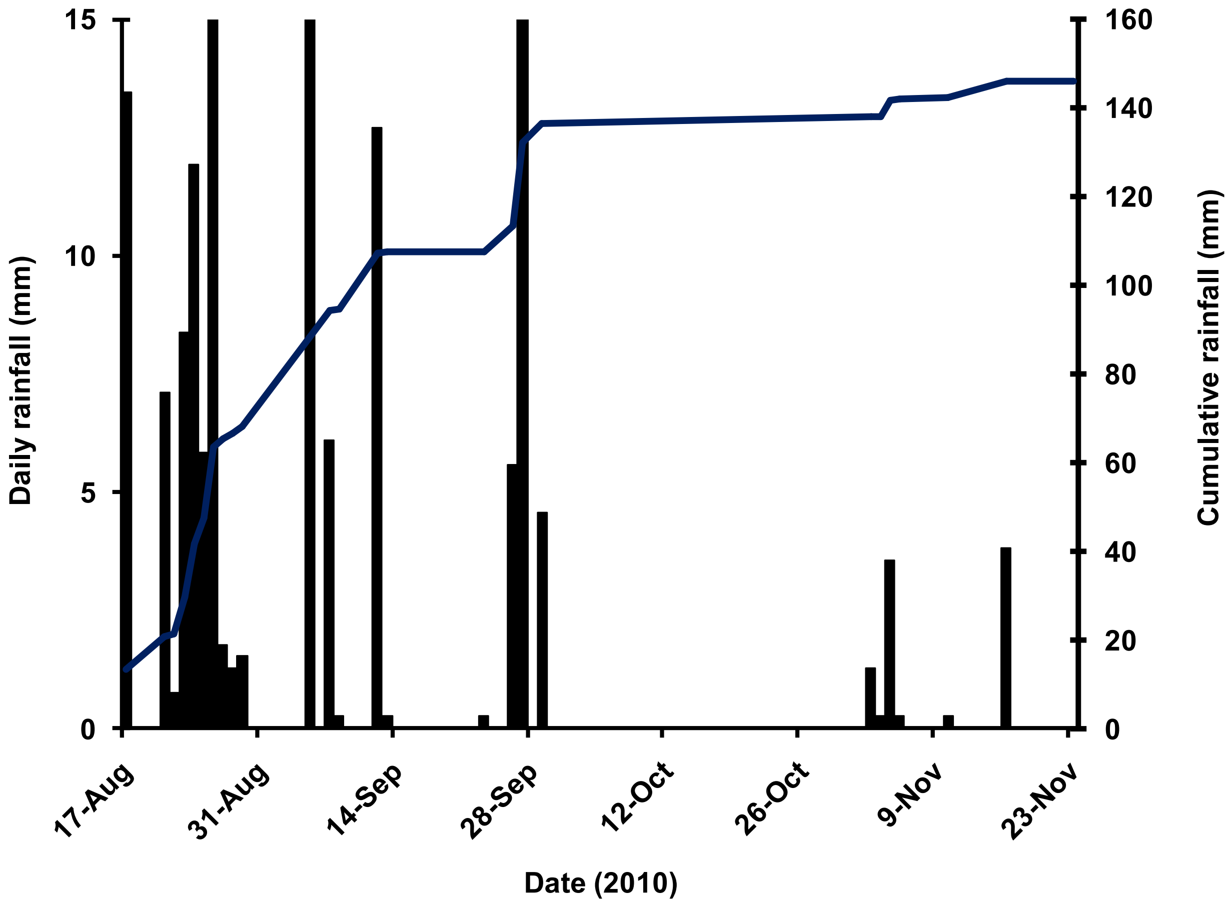

Figure 1. Daily and cumulative rainfall, during 17 August through 23 November 2010.

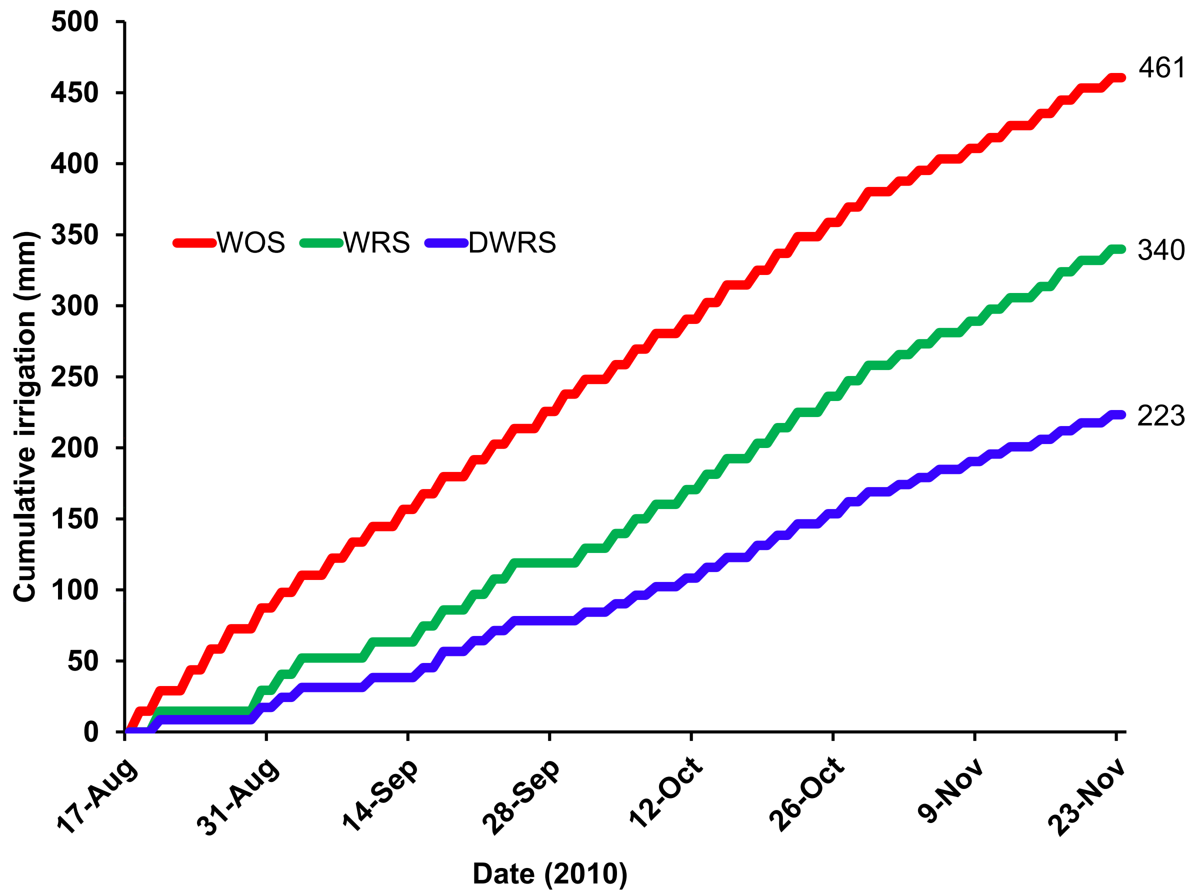

Figure 2. Cumulative irrigation applied from 17 August through 23 November 2010 by time-based treatments WOS = without sensor, WRS = with rain sensor, and DWRS = deficit with rain sensor.

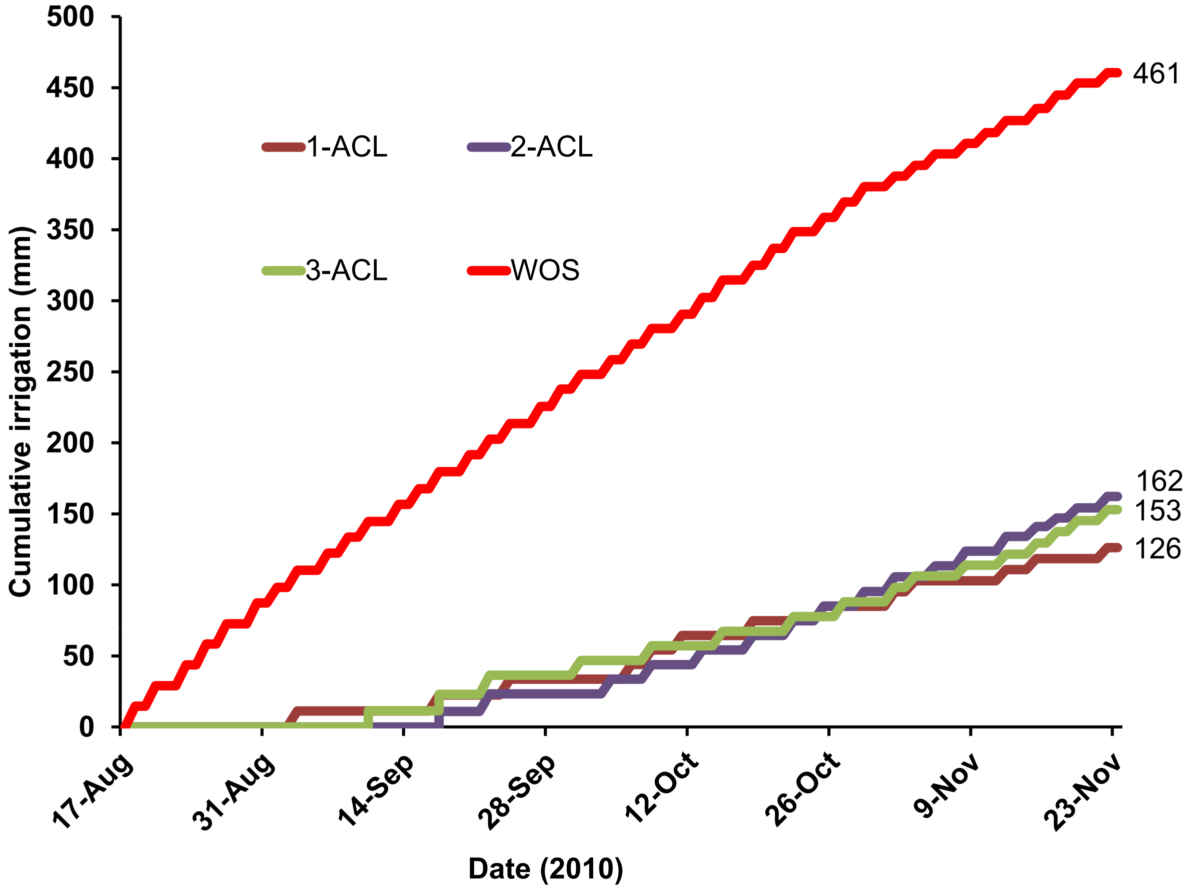

Figure 3. Cumulative irrigation applied by replicates of ACL = soil moisture sensors system-based treatment from brand Acclima, compared to WOS = time-based control treatment without sensor, from 17 August through 23 November 2010. (Numbers before -ACL indicate an arbitrary number for the different replicates.)

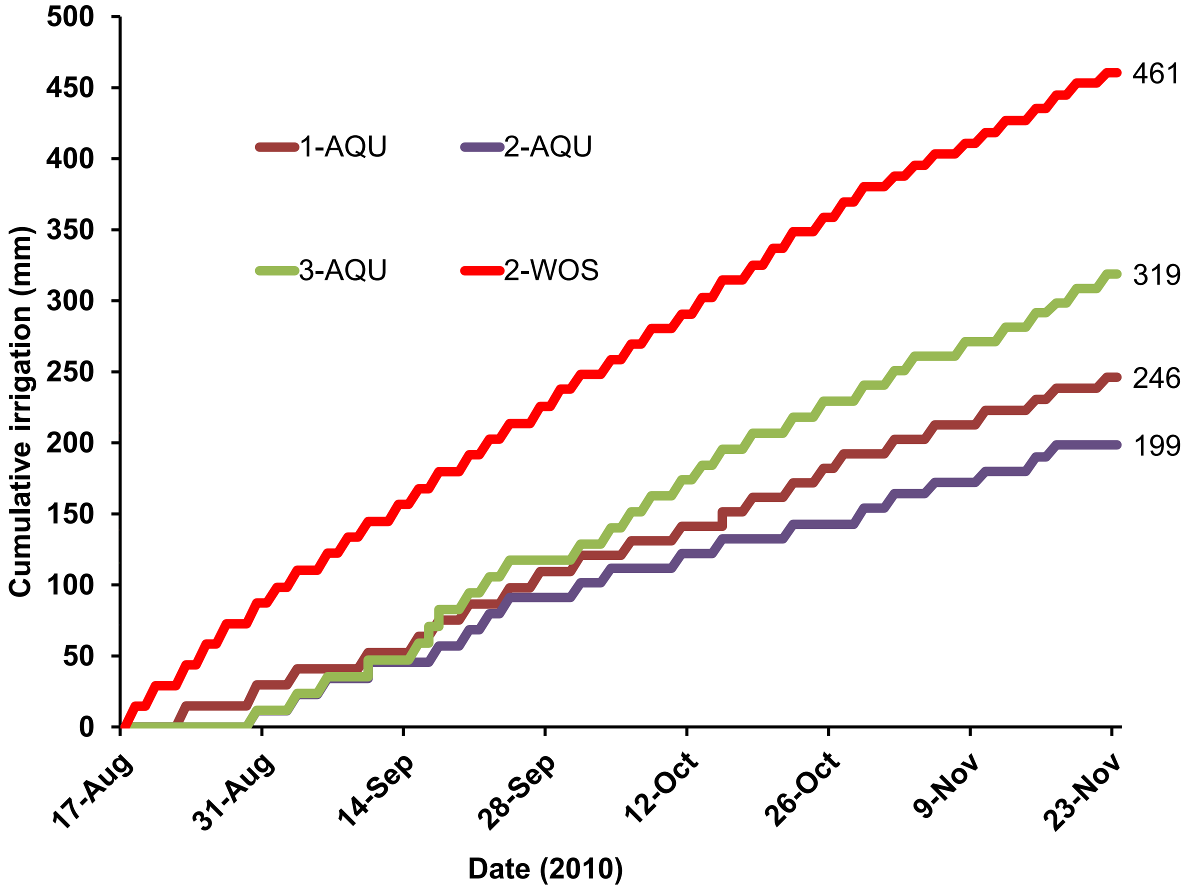

Figure 4. Cumulative irrigation applied by replicates of AQU = soil moisture sensors system-based treatment from brand Aquaspy, compared to WOS = time-based control treatment without sensor, from 17 August through 23 November 2010. (Numbers before -AQU indicate an arbitrary number for the different replicates.)

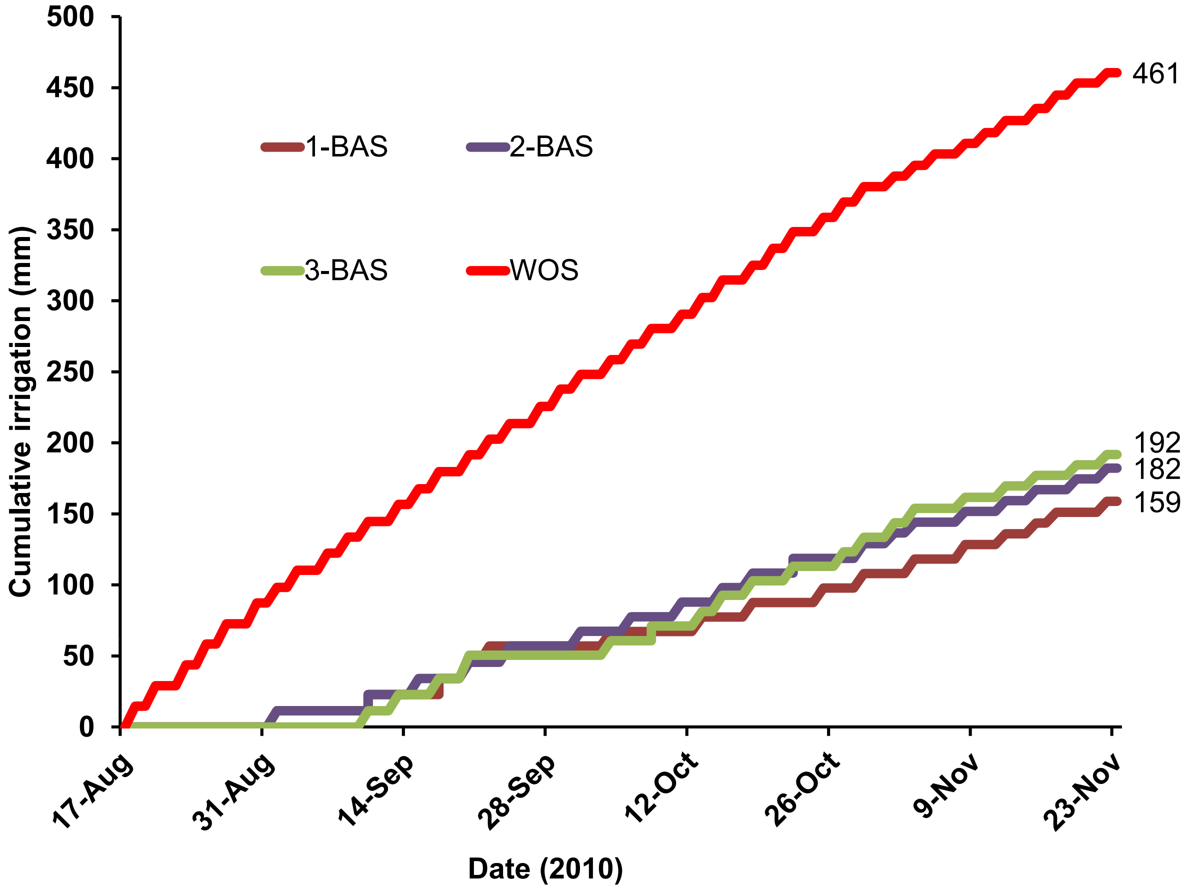

Figure 5. Cumulative irrigation applied by replicates of BAS = soil moisture sensors system-based treatment from brand Baseline, compared to WOS = time-based control treatment without sensor, from 17 August through 23 November 2010. (Numbers before -BAS indicate an arbitrary number for the different replicates.)

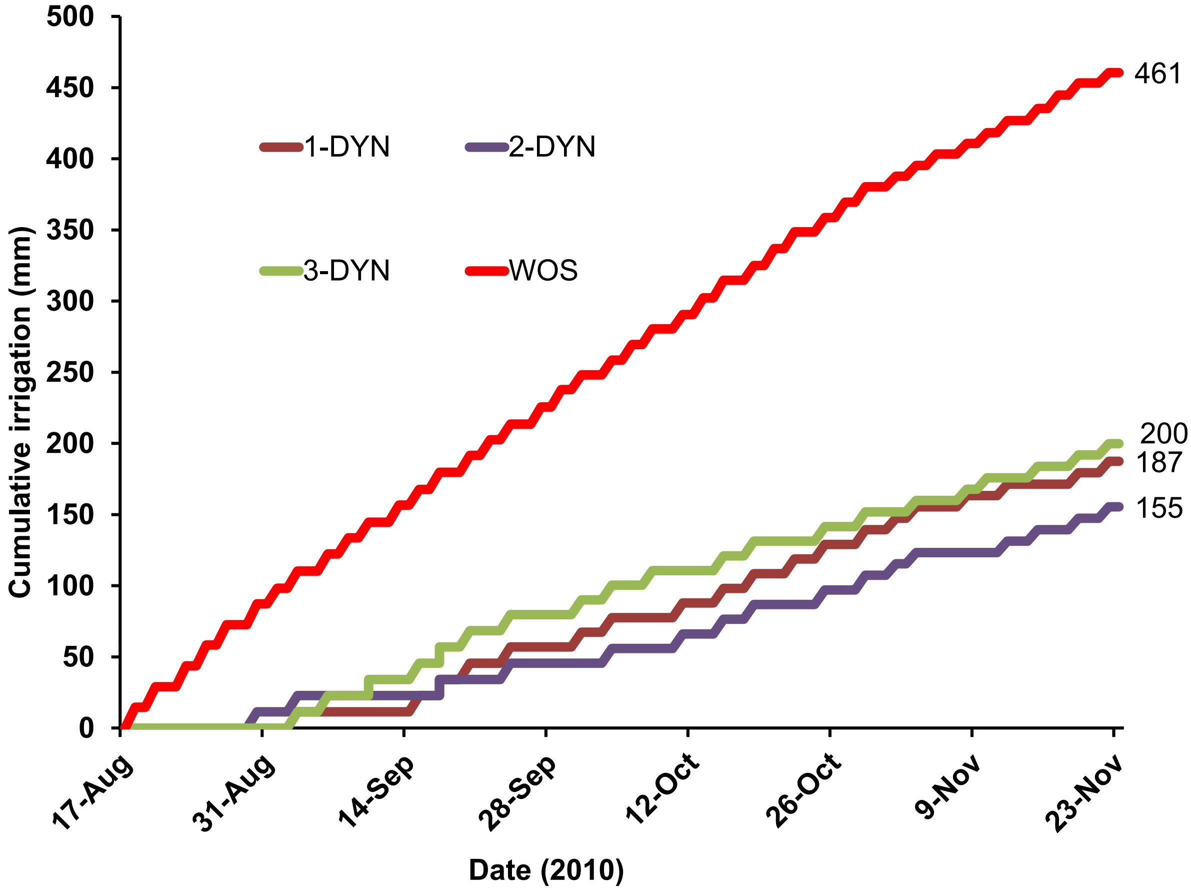

Figure 6. Cumulative irrigation applied by replicates of DYN = soil moisture sensors system-based treatment from brand Dynamax, compared to WOS = time-based control treatment without sensor, from 17 August through 23 November 2010. (Numbers before -DYN indicate an arbitrary number for the different replicates.)

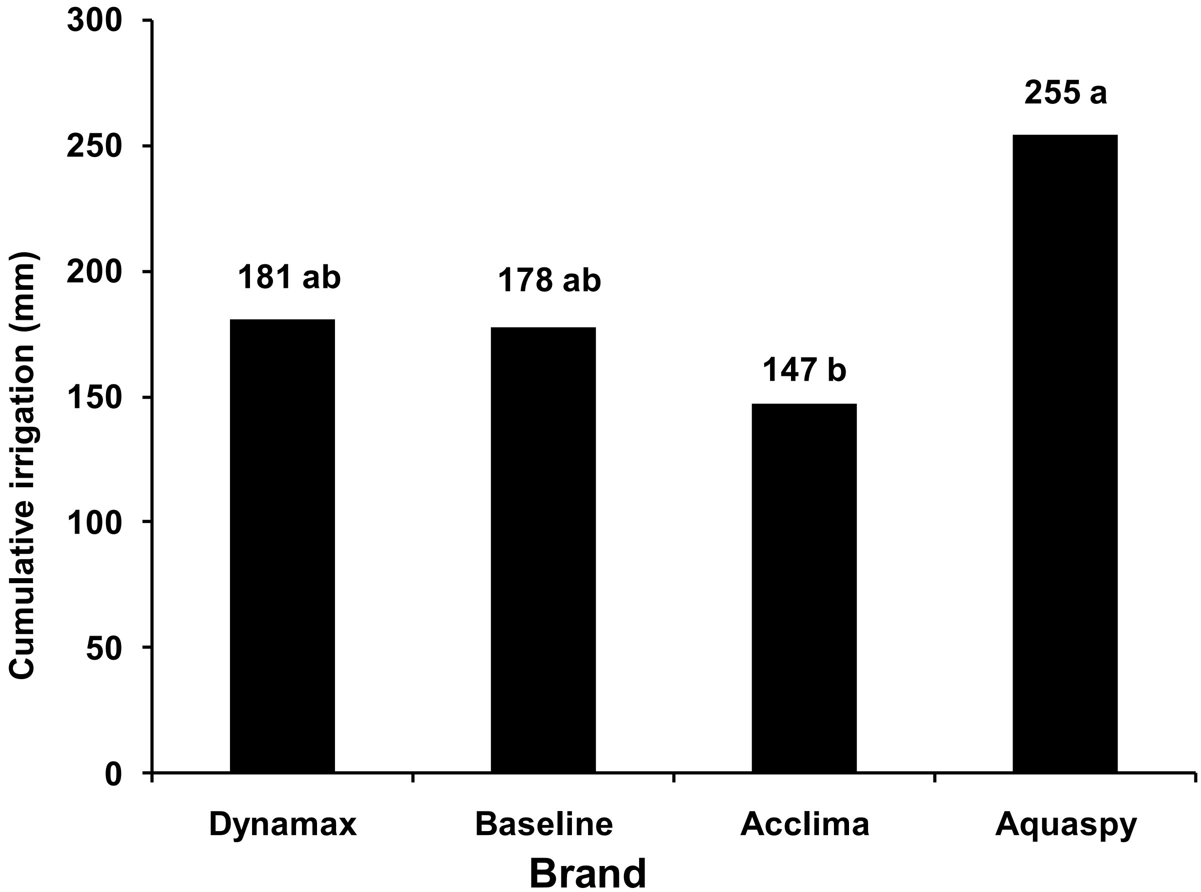

Figure 7. Average irrigation depth applied by brand during 17 August through 23 November 2010.

Developing a Model Irrigation Dissemination Program for Homeowners

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Abstract. *Over the past 60 years, research and demonstration projects have shown that using evapotranspiration (ET) based irrigation schedules can save significant amounts of water. In urban settings, automatic irrigation systems typically are improperly programmed and "over-irrigate" (and waste) 20%-50% of the water applied. Many municipalities have struggled to develop outdoor water conservation programs to address these problems, with mixed results. This paper discusses an innovative approach for providing ET-based irrigation schedules.*

Keywords. *Landscape Irrigation, Irrigation Scheduling, Homeowners, Evapotranspiration*

TexasET Approach

The Texas Evapotranspiration (TexasET) Network was developed in 1994 by the Texas A&M Agrilife Extension Service in order to promote ET-based irrigation water management. The TexasET Network and website (http://TexasET.tamu.edu) is a collaboration of ET weather stations around Texas. Unlike other states which fund state-wide ET Networks, TexasET receives no State funding to maintain the network. The TexasET Networks operation depends upon local sponsors to purchase the weather stations and cover communication and maintenance costs, thereby limiting its coverage within Texas.

The TexasET website, in addition to providing daily summaries of reference evapotranspiration (ETo) and weather data (temperature, relative humidity, solar radiation, wind speed and rainfall) contains tools to assist users in determining their irrigation requirements. These calculators are designed for home watering, turf and landscape irrigation, and crop irrigation (not to be discussed further in this paper).

Home Watering

The home watering tool is a simple calculator developed for homeowners. Once a location/weather station is selected the homeowner selects how much sunlight exposure their lawn receives choosing from full sun, part sun and shade. Then they select what type of turfgrass they have in their yard, choosing from Buffalo, Bermuda, Zoysia and St. Augustine. In scientific terms these are all warm season turf grasses (most commonly found in Texas) whose plant water requirement is the same, but homeowner are given the choice since they may not know their turf is a warm season variety. Once these two factors are selected, a water requirement for the turf is calculated. Next the effective rainfall is calculated (if any) then subtracted from the water requirement of the turf to produce the irrigation requirement, in inches.

Turf & Landscape Irrigation

The turf and landscape irrigation tool takes calculating irrigation requirements a step further. Like the home watering calculator, the irrigator first selects his/her closest ET weather station. They then select their plant coefficient by choosing one of five different plant types including: warm season turf, cool season turf, frequent watering plants, occasional watering plants and natural rainfall type plants. Next an adjustment factor is chosen for the desired plant quality ranging from maximum to low. This assumes the irrigator is much more familiar plant water requirements and is able to select the proper plant type and landscape conditions affecting plant quality. Due to the scarcity of weather stations on the network, the irrigator can then choose to use the calculated effective rainfall for the site or enter in more localized rainfall data to determine what the total water requirement is, in inches.

Frequent users of the TexasET website have the option to create online landscape profiles, following steps similar to those used in the turf and landscape calculator in order to receive emailed irrigation recommendations on user defined intervals. However, due to the limited number of stations on the network, recommendations are given in inches without rainfall automatically deducted. Although given the rainfall recorded at the ET weather station, this allows users to use the most localized rainfall data (weather service, backyard rain gauge, ect.) available to them to determine irrigation requirements.

Challenges of Using TexasET

Many homeowners understand the irrigation recommendations produced by the TexasET Network. However, the challenge to homeowners becomes implementing the irrigation recommendation, particularly due to many homeowners not knowing the precipitation rates of their irrigation stations. Since irrigation controllers are programmed for runtimes (minutes) and not irrigation requirements (inches), homeowners do not effectively know how to implement the schedule. Texas regulations have made it easier for homeowners with newer irrigation systems (installed after January 2009) since irrigation scheduling information is required to be given to the irrigation system owner following completion of the installation. Larger municipal water utilities offer auditing and irrigation evaluation services to customers in higher water use tiers but smaller residential customers might often have to hire an irrigation professional (such as the Licensed Irrigator in Texas) or Certified Landscape Irrigation Auditor, which can be expensive in some cases.

Water My Yard Program

One possible solution to help homeowners determine when and how long to run their irrigation systems while using science based methods is the Water My Yard Program (http://WaterMyYard.org). The Water My Yard program website employs simple, intuitive images and information prompts for homeowners to get recommendations on how long (in minutes) to run their irrigation system. The program was launched in May 2013 as a joint effort of the Irrigation Technology Program of the Texas A&M Agrilife Extension Service (Extension) and the North Texas Municipal Water District.

The North Texas Municipal Water District (NTMWD) covers 1,600 square miles and provides to water services to 1.6 million residents of North Texas through 13 member cities. NTMWD provides the majority of water from surface water storage in Lake Lavon. With persistent drought over the last few years, lake levels have dropped resulting in mandatory water restrictions, particularly for landscape irrigation. Most restrictions have limited outdoor watering to two (2) days a week irrigation with recent restrictions allowing only one (1) day a week watering.

Working with Extension, NTMWD purchased and installed seven (7) ET Weather Stations. Locations were chosen based on elevation, microclimates, district property, and variations in typical rainfall patterns. Weather station data is collected daily as a part of the TexasET Network to calculate daily ETo. A custom interactive map was created (Figure 1.) for homeowners to select their location within the district while showing them which weather station is used for their area.

As discussed, precipitation rate is needed to produce an irrigation runtime. Once their location is selected, the homeowner is prompted to enter their precipitation rate (Figure 2.). If the precipitation rate is not known, they are given instructions on how to conduct a catch can test in their yard to calculate their precipitation rate or they can select their sprinkler type. Working with state and local irrigation associations and sprinkler manufacturer representatives, a list of irrigation systems was developed to describe turf grass irrigation systems in the area (Figure 3.). These include the major types of emission devices used such as spray heads, rotors, multi-stream rotors and drip irrigation (required in some landscapes as per Texas Rules and Regulations). After the sprinkler type is selected, the spacing between sprinklers (or emitters) and the manufacturer is selected in order to fine tune the precipitation rate for calculating runtime (Figure 4.). Once the precipitation rate is set, a runtime can be calculated.

In order to calculate the runtime, assumptions have to be made to make this simple for homeowners. The obvious first assumption is that the homeowner is watering a warm season turf grass, however residential turf does not need its maximum water requirement to maintain acceptable turf quality like a golf course green or a sports field. Typically we can reduce water requirements by 40% and still maintain acceptable turf quality. This is typically reflected as an adjustment factor of “Normal Quality” or 60% of turfgrass evapotranspiration (ETc). In the case of NTMWD, a shift from Stage 2 Water Restrictions (2 Days a Week Watering) to Stage 3 Water Restrictions (1 Day a Week

Watering) requires a 10% reduction in water use as a part of the districts drought management plan. During these periods the adjustment factor can be reduced to a “Low Quality” or 50% of turfgrass ETc. This will keep the turfgrass alive but may result in some mild visual signs of turf stress during peak ET in the summer. Taking the adjustment factors into account along with user defined precipitation rate and localized weather station rainfall, the Water My Yard Program can calculate weekly irrigation runtimes (Figure 5.). Once a runtime recommendation has been calculated for a site, the homeowner can then sign up for weekly irrigation runtime emails to be received every Monday.

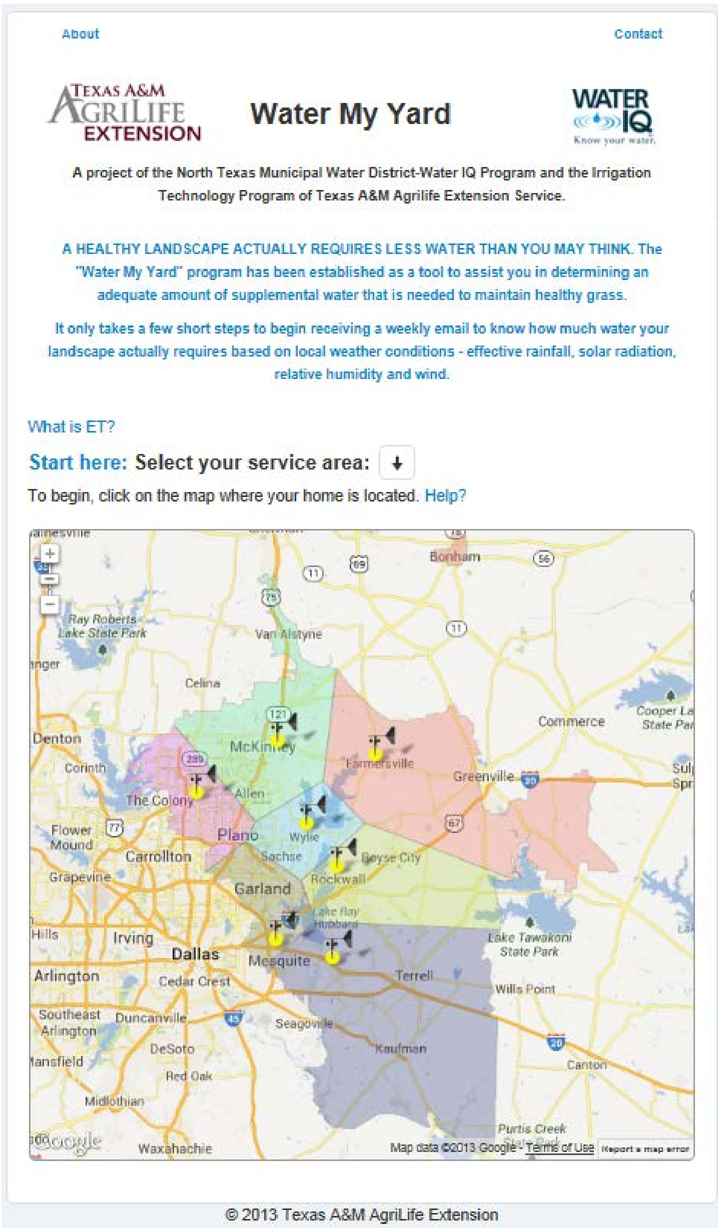


Figure 1. Water My Yard Homepage-Map

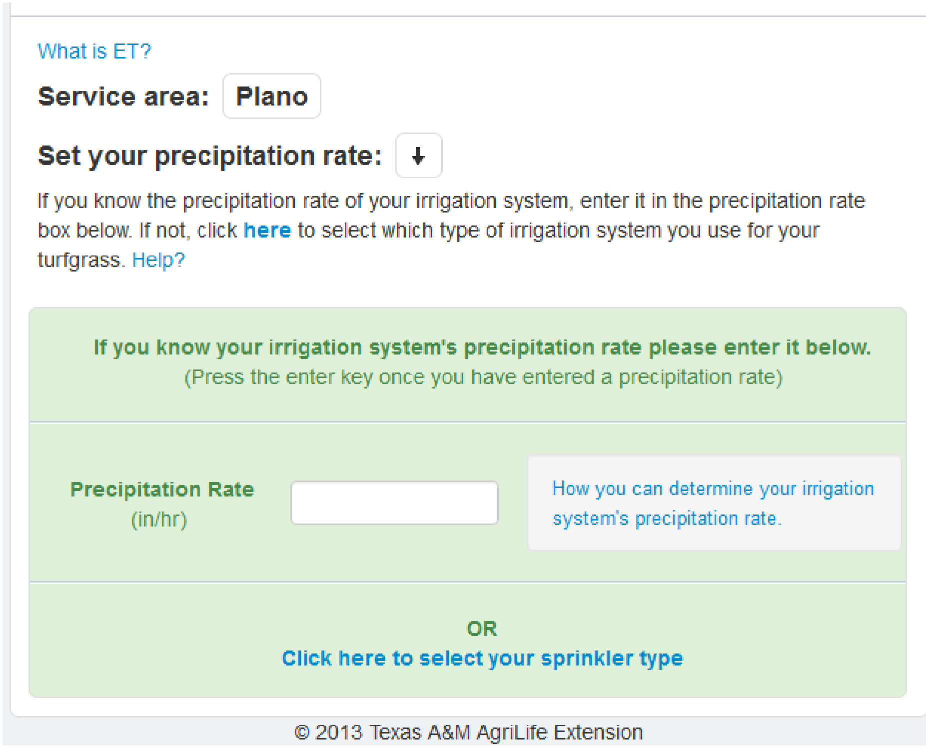


Figure 2. Water My Yard- Enter Precipitation Rate

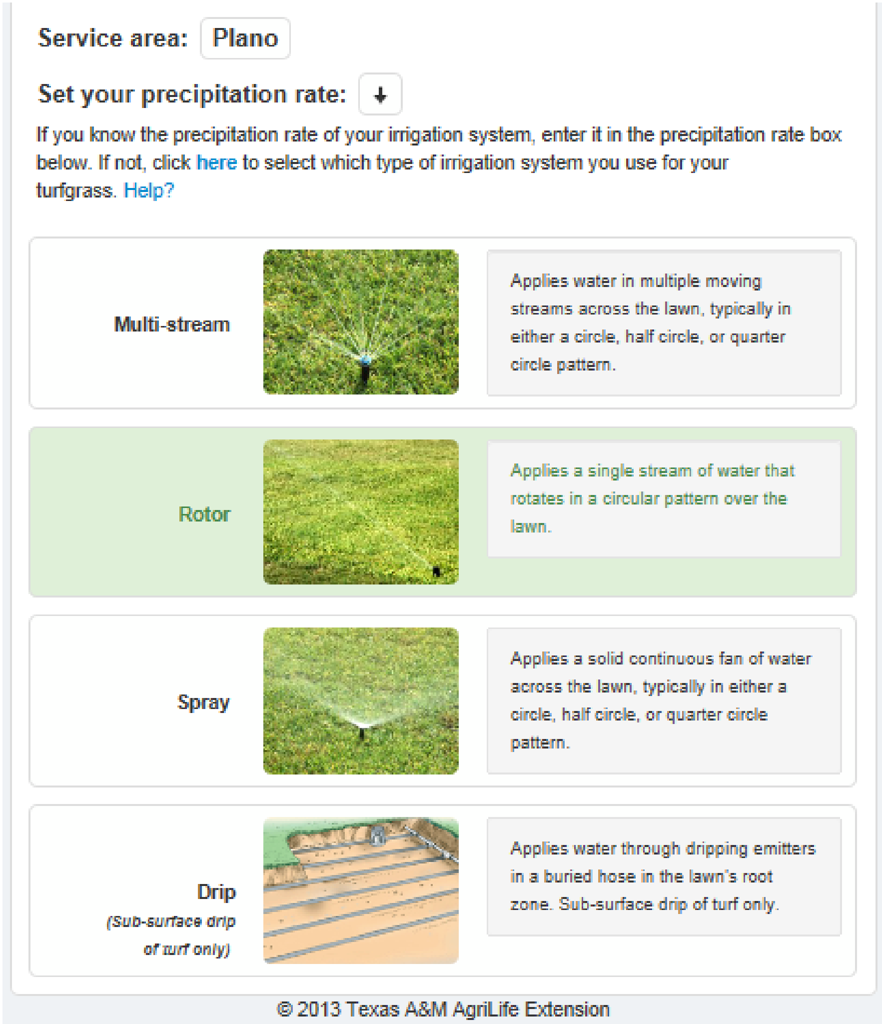


Figure 3. Water My Yard- Select a Sprinkler Type

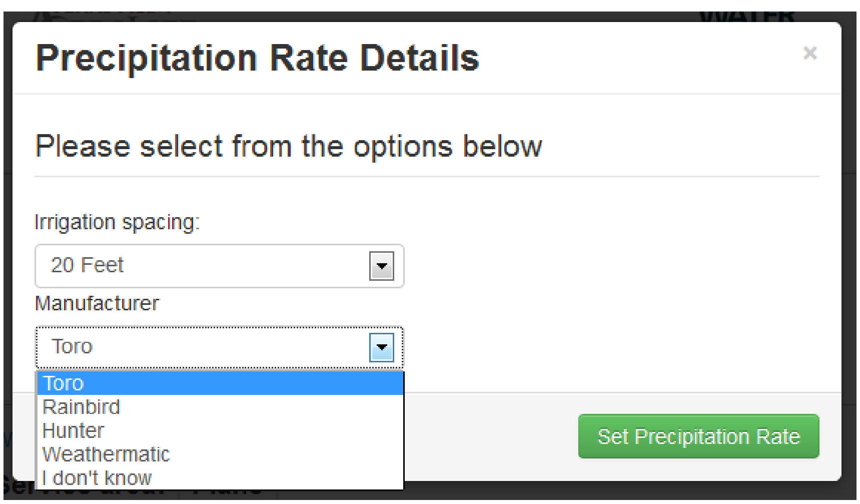
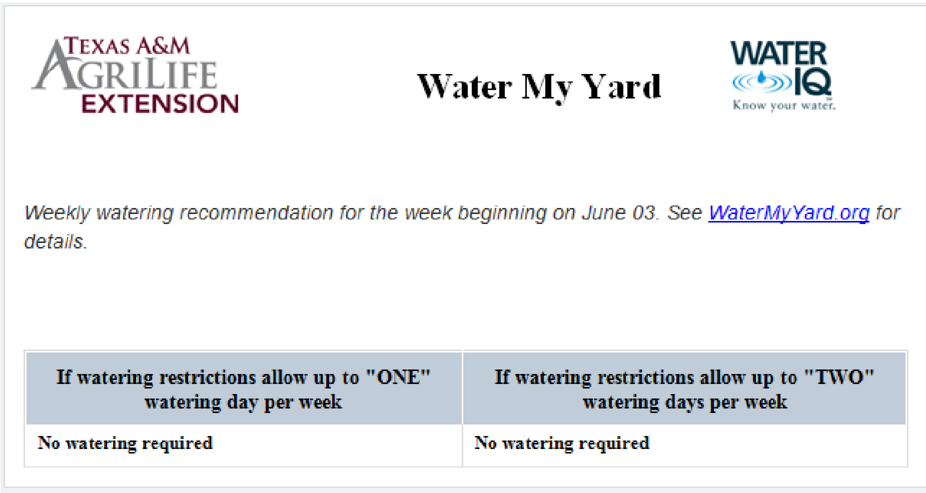


Figure 4. Water My Yard- Select a Sprinkler Details



If watering restrictions allow up to "ONE" watering day per week	If watering restrictions allow up to "TWO" watering days per week
No watering required	No watering required

Figure 5. Water My Yard- Recommendation

Conclusion

The Water My Yard program as of October 1, 2013 has 603 user accounts within the North Texas Municipal Water District since coming online 4 months ago. Three additional water utilities and water districts have adopted the concept and will be joining the Water My Yard program during the Fall of 2013. Further research and analysis needs to be conducted to determine optimal density of ET weather stations and rain gauges based on spatial variability in urban environments. Refinements may also have to be made to the irrigation system options by expanding sprinkler criteria to better fine tune runtime recommendations and more outreach on educating homeowners how to calculate the true precipitation rate of their irrigation system.

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Texas A&M Agrilife Extension Service. TexasET Network. http://TexasET.tamu.edu . June 2013.

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Can ET-Based Irrigation Controllers Meet Texas Landscape Needs?

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Abstract. *A smart controller testing facility was established by the Irrigation Technology Center at Texas A&M University in College Station in 2008. The objectives were to (1) evaluate smart controller testing methodology and to (2) determine their performance and reliability under Texas conditions from an "end-user" point of view. The "end-user" is considered to be the landscape or irrigation professional (such as the Licensed Irrigator in Texas) installing the controller. This report summaries the performance of nine smart controllers over an eight month growing season in 2012. Controllers were programmed based on a virtual landscape that evaluated controller performance using multiple plant types (flowers, turf, groundcover, small and large shrubs), soil types (sand, loam and clay), root zone depths (3 to 20 inches) and other site specific characteristics. Controllers were divided into 2 categories, those which utilize on-site sensors to calculate or adjust ET or runtimes; and those which ET values are sent via cellular, radio or the internet. Controller performance was compared to total ETo, plant water requirement (ETc) and the weekly irrigation recommendation of the TexasET Network (http://TexasET.tamu.edu). Results so far indicate some controllers may be able to meet Texas Landscape needs. Significant seasonal differences in controller performance were also found. The 2012 results show trends in controller performance compared to 2010 and 2011.*

Keywords. *Landscape Irrigation, Irrigation Scheduling, Smart Controllers, Evapotranspiration, Water Conservation*

INTRODUCTION

The term *smart irrigation controller* is commonly used to refer to various types of controllers that have the capability to calculate and implement irrigation schedules automatically and without human intervention. Ideally, smart controllers are designed to use site specific information to produce irrigation schedules that closely match the day-to-day water use of plants and landscapes. In recent years, manufacturers have introduced a new generation of smart controllers which are being promoted for use in both residential and commercial landscape applications.

However, many questions exist about the performance, dependability and water savings benefits of smart controllers. Of particular concern in Texas is the complication imposed by rainfall. Average rainfall in the State varies from 56 inches in the southeast to less than eight inches in the western desert. In much of the State, significant rainfall commonly occurs during the primary landscape irrigation seasons. Some Texas cities and water purveyors are now mandating smart controllers. If these controllers are to become requirements across the state, then it is important that they be evaluated formally under Texas conditions.

CLASSIFICATION OF SMART CONTROLLERS

Smart controllers may be defined as irrigation system controllers that determine runtimes for individual stations (or “hydrozones”) based on historic or real-time ETo and/or additional site specific data. We classify smart controllers into four (4) types (see Table 1): Historic ET, Sensor-based, ET, and Central Control.

Many controllers use ETo (potential evapotranspiration) as a basis for computing irrigation schedules in combination with a root-zone water balance. Various methods, climatic data and site factors are used to calculate this water balance. The parameters most commonly used include:

- ET (actual plant evapotranspiration)
- Rainfall
- Site properties (soil texture, root zone depth, water holding capacity)
- MAD (managed allowable depletion)

The IA SWAT committee has proposed an equation for calculating this water balance. For more information, see the IA’s website: http://irrigation.org.

Table 1.Classification of smart controllers by the method used to determine plant water requirements in the calculation of runtimes.

Historic ET	Uses historical ET data from data stored in the controller
Sensor-Based	Uses one or more sensors (usually temperature and/or solar radiation) to adjust or to calculate ETo using an approximate method
ET	Real-time ETo (usually determined using a form of the Penman equation) is transmitted to the controller daily. Alternatively, the runtimes are calculated centrally based on ETo and then transmitted to the controller.
On-Site Weather Station (Central Control)	A controller or a computer which is connected to an on-site weather station equipped with sensors that record temperature, relative humidity (or dew point temperature) wind speed and solar radiation for use in calculating ETo with a form of the Penman equation.

MATERIALS AND METHODS

Testing Equipment and Procedures

Two smart controller testing facilities have been established by the ITC at Texas A&M University in College Station: an indoor lab for testing ET-type controllers and an outdoor lab for sensor-based controllers. Basically, the controllers are connected to a data logger which records the start and stop times for each irrigation event and station (or hydrozone). This information is transferred to a database and used to determine total runtime and irrigation volume for each irrigation event. The data acquisition and analysis process is illustrated Figure A-1 . Additional information and photographs of the testing facilities are provided in the Appendix.

Smart Controllers

Nine (9) controllers were provided by manufacturers for the Year 2012 evaluations (Table 2). Each controller was assigned an ID for reporting purposes. Table 2 lists each controller's classification, communication method and on-site sensors, as applicable. The controllers were grouped by type for testing purposes

Table 2. The controller name, type, communication method, and sensors attached of the controllers evaluated in this study. All controllers were connected to a rain shut off device unless equipped with a rain gauge.

Controller ID	Controller Name	Type	Communication Method	On-Site Sensors[1]	Rain Shutoff
A	ET Water	ET	Pager	None	✓
B	Rainbird ET Manager Cartridge	ET	Pager	Tipping Bucket Rain Gauge	
C	Hunter ET System	Sensor Based	-	Tipping Bucket Rain Gauge, Pyranometer, Temperature/ RH, Anemometer	
D	Hunter Solar Sync	Sensor Based	-	Pyranometer	✓
E	Rainbird ESP SMT	Sensor Based	-	Tipping Bucket Rain Gauge, Temperature	
F	Accurate WeatherSet	Sensor Based	-	Pyranometer	✓
G	Weathermatic Smartline	Sensor Based	-	Temperature	✓
H	Toro Intellisense	ET	Pager	None	✓
I	Irritrol Climate Logic	Sensor Based	-	Temperature, Solar Radiation	✓

[1] Rain shut off sensors are not considered On-Site Sensors for ET Calculation or runtime adjustment

Definition of Stations (Zones) for Testing

Each controller was assigned six stations, each station representing a virtual landscaped zone

(Table 3). These zones are designed to represent the range in site conditions commonly found in Texas, and provide a range in soil conditions designed to evaluate controller performance in shallow and deep root zones (with low/high water holding capacities). Since we do not recommend that schedules be adjusted for the DU (distribution uniformity), the efficiency was set to 100% if allowed by the controller.

Programing the smart controllers according to these virtual landscapes proved to be problematical, as only two controllers (E and H) had programming options to set all the required parameters defining the landscape (see Table 4). It was impossible to see the actual values that two controllers used for each parameter or to determine how closely these followed the values of the virtual landscape.

One example of programming difficulty was entering root zone depth. Four of the nine controllers did not allow the user to enter the root zone depth (soil depth). Another example is entering landscapes plant information. Three of the controllers did not provide the user the ability to see and adjust the actual coefficient (0.6, 0.8, etc.) that corresponds to the selected plant material (i.e., fescue, cool season grass, warm season turf, shrubs, etc.).

Thus, we programmed the controllers to match the virtual landscape as closely as was possible. Manufacturers were given the opportunity to review the programming, which three did. Five of the remaining manufacturers provided to us written recommendations/instructions for station programming, and one manufacturer trusted our judgment in controller programming.

Table 3. The Virtual Landscape which is representative of conditions commonly found in Texas.

	Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
Plant Type	Flowers	Turf	Turf	Groundcove r	Small Shrubs	Large Shrubs
Plant Coefficient (Kc)	0.8	0.6	0.6	0.5	0.5	0.3
Root Zone Depth (in)	3	4	4	6	12	20
Soil Type	Sand	Loam	Clay	Sand	Loam	Clay
MAD (%)	50	50	50	50	50	50
Adjustment Factor (Af)	1.0	0.8	0.6	0.5	0.7	0.5
Precipitation Rate (in/hr)	0.2	0.85	1.40	0.5	0.35	1.25
Slope (%)	0-1	0-1	0-1	0-1	0-1	0-1

Table 4. The parameters which the end user could set in each controller directly identified by the letter “x.”

Controller	Soil Type	Root Zone Depth	MAD	Plant Type	Crop Coefficient	Adjustment Factor	Precipitation Rate	Zip Code or Location	Runtime
A	X	X	X	X		X	X	X	
B[1]	-	-	-		X	-	-	X	X
C	X			X	X	X	X		
D[2]	-	-	-		-	-	-	X	X
E	X	X		X	X	X	X		
F[2]				X					X
G	X			X	X	X	X	X	
H	X	X	X	X	X	X	X	X	
I[2]	-	-	-		-	-	-	X	X

[1] Irrigation amount was set based on plant available water
[2] Controller was programmed for runtime and frequency at peak water demand (July).

Testing Period

The controllers were set up and run from April 30 to September 30 and from October 1 to December 2, 2012. Controller performance is reported over seasonal periods. For the purposes of this report, seasons are defined as follows:

- Summer: April 30 to September 30 (153 Days),
- Fall: October1 to December 2 (62 Days).

ETo and Recommended Irrigation

ETo was computed from weather parameters measured at the Texas A&M University Golf Course in College Station, TX which is a part of the TexasET Network (http://TexasET.tamu.edu). The weather parameters were measured with a standard agricultural weather station (Campbell Scientific Inc) which records temperature, solar radiation, wind and relative humidity. ETo was computed using the standardized Penman-Monteith method.

TexasET and the Plant Water Requirement Calculator

In this report, smart controller irrigation volumes are compared to the recommendations of the TexasET Network and Website generated using the *Landscape Plant Water*

Requirement Calculator (http://TexasET.tamu.edu) on a weekly basis. This weekly water balance approach is used for the weekly irrigation recommendations generated by TexasET for users that sign-up for automatic emails. The calculation uses the standard equation:

$$ETc = (ETo \times Kc \times Af) - Re \qquad \text{(Equation 1)}$$

where: ETc = irrigation requirement
ETo = reference evapotranspiration
Kc = crop coefficient
Af = adjustment factor
Re = effective rainfall

Due to the lack of scientifically derived crop coefficients for most landscape plants, we suggest that users classify plants into one of three categories based on their need for or ability to survive with frequent watering, occasional watering and natural rainfall. Suggested crop coefficients for each are shown in Table 5.

In addition to a Plant Coefficient, TexasET users have the option of applying an *Adjustment Factor*. This can be used to make adjustments for site factors such as microclimates, allowable stress, or desired plant quality. For most home sites, a *Normal Adjustment Factor* (0.6) is recommended in order to promote water conservation, while an adjustment factor of 1.0 is recommended for sports athletic turf. Table 6 gives the adjustment factor in terms of a plant quality factor.

A weekly irrigation recommendation was produced using equation (1) following the methodology discussed above. The Af used are shown in Table 3. Effective rainfall was calculated using the relationships shown in Table 7.

Table 5. Landscape Plant Water Requirements Calculator Coefficients

Plant Coefficients		**Example Plant Types**
Warm Season Turf	0.6	Bermuda, St Augustine, Buffalo, Zoysia, etc.
Cool Season Turf	0.8	Fescue, Rye, etc.
Frequent Watering	0.8	Annual Flowers
Occasional Watering	0.5	Perennial Flowers, Groundcover, Tender Woody Shrubs and Vines
Natural Rainfall	0.3	Tough Woody Shrubs and Vines and non-fruit Trees

Table 6. Adjustment Factors in terms of "Plant Quality Factors."

Maximum	1.0
High	0.8
Normal	0.6
Low	0.5
Minimum	0.4

Table 7. TexasET Effective Rainfall Calculator

Rainfall Increment	% Effective
0.0" to 0.1"	0%
0.1" to 1.0"	100%
1.0" to 2.0"	67%
Greater than 2"	0%

Irrigation Adequacy Analysis

The purpose of the irrigation adequacy analysis is to identify controllers which over or under irrigate landscapes. An uncertainty in calculating a water balance is effective rainfall, how much of rainfall is credited for use by the plant. Further complicating rainfall is the use and performance of rain shut off devices.

For this study we broadly define irrigation ***adequacy*** as the range between taking 80% credit for all rainfall ($R_e = 0.8$) and taking no credit for rainfall ($R_e = 0$). These limits are defined as:

Extreme Upper Limit = ETo x Kc (eq. 2)
Adequacy Upper Limit = ETo x Kc x Af (eq. 3)
Adequacy Lower Limit = ETo x Kc x Af - Net (80%) Rainfall (eq. 4)
Extreme Lower = ETo x Kc x Af - Total Rainfall (eq. 5)

The adequacy upper limit is defined as the plant water requirement (eq. 3) without rainfall. Irrigation volumes greater than the upper limit are classified as ***excessive***. The adequacy lower limit is defined as the plant water requirements minus Net Rainfall (eq 4). The IA SWAT Protocol defines net rainfall as 80% of rainfall. Irrigation volumes below than the adequacy lower limit are classified as ***inadequate***.

For comparison purposes, extreme limits are defined by taking no credit for rainfall (upper) and total rainfall (lower). These limits are the maximum and minimum possible plant water requirements.

RESULTS

Results from the Year 2012 evaluation periods are summarized in Tables 9, 10 and 11 by season.

TexasET Comparisons

Controller performance during the Summer evaluation period (April 30-September 30, 2012) was good.

Controllers Passing
Controller G had all six stations within the recommendations of TexasET

Good Performers
Controller B had five stations that were within TexasET.

Poor Performers
Controllers D and I produced irrigation volumes in excess of ETo for two stations.
Controller D had six stations that were in excess of ETc.
Controller D, F, H and I did not produce any stations within TexasET.

Controller Performance during the Fall evaluation period (October 1-December 2, 2012) was generally poor.

Controllers Passing
None

Best Performer
Controller C had three stations that were within TexasET.

Poor Performers
Controllers D produced irrigation volumes in excess of ETo.
Controllers D and F produced irrigation volumes in excess of ETc.
Controller B, D and H did not produce any stations within TexasET.

Tables 12-14 show the irrigation **adequacy** analysis for each station during the two seasonal periods. During the Summer period, four (4) controllers applied excessive amounts of irrigation for one or more stations with one (1) controller applying excessive amounts for all six (6) stations. Only three (3) controllers applied excessive amounts of irrigation during the Fall period, with one (1) controller applying excessive amounts for all six (6) station. No controllers during the study period applied inadequate amounts of irrigation.

Appendix B contains daily ET readings from controllers and the TexasET Network graphed with daily rainfall totals during the entire evaluation period (Figure B-1) and as a percentage of daily ETo (Figure B-2). Controller ET values appeared erratic and inconsistent compared to TexasET throughout the study period; however all controllers consistently show decreases in ETo values during days which rainfall occurred.

Controller Problems

Two controllers experienced problems during the course of the study.

1. Controller B had poor signal accuracy during the study dropping down as low as 17% at some times. The signal provider was notified and adjustments were made in the signal settings and an upgraded antenna was installed. Signal accuracy increased after adjustments.

2. Controller H experienced communication problems multiple times throughout the study. Controller alerts (beeping) occurred on at least 2 occasions during the evaluation period. The manufacturer was notified of the problem and a signal amplifier was installed on the controller. However, it was later determined that the problem was a result of temporary poor signal service by the signal provider company in the testing area (a bad tower).

Table 8. Entire Testing Period Performances. Irrigation amount (inches) applied for each controller station. Yellow denotes values within +/- 20 % of TexasET Recommendation. Red indicates values in excess of ETc.

Controller	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	26.79	16.66	12.51	11.21	10.50	7.50
B	24.75	13.35	9.70	6.93	8.44	3.55
C	19.31	9.11	5.29	5.10	5.27	0.57
D	68.32	43.52	33.46	20.89	27.96	13.91
E	30.18	16.97	8.90	4.85	7.39	0.00
F	28.72	24.54	27.81	10.18	16.29	10.46
G	22.49	13.02	9.76	6.62	9.47	3.73
H	27.89	17.87	12.40	9.41	12.78	5.53
I	60.31	20.42	15.04	9.32	13.67	6.38
Total ETo[1]	39.60					
Total Rain[2]	16.41					
Total ETc[3]	31.68	23.76	23.76	19.80	19.80	11.88
TexasET Recommendation	21.67	11.16	7.84	5.26	7.59	2.94

[1] Total ETo calculated using the standardized Penmen-Monteith method using weather data collected at the Texas A&M University Golf Course, College Station, Texas.
[2] Total Rainfall collected from TexasET Network Weather Station "TAMU Golf Course"
[3] Rainfall and Adjustment Factor not included in this calculation

Table 9. Summer Performances. Irrigation amount (inches) applied for each controller station. Yellow denotes values within +/- 20 % of TexasET Recommendation. Red indicates values in excess of ETc

Controller	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	22.00	14.28	10.83	9.28	9.45	7.50
B	20.33	10.55	7.65	5.46	6.20	3.55
C	15.67	7.59	4.58	4.13	4.68	0.57
D	55.31	35.11	26.90	16.72	22.35	11.19
E	25.92	14.66	7.80	4.60	6.60	0.00
F	24.90	18.70	22.91	8.44	13.51	8.67
G	18.50	10.54	7.90	5.46	7.66	2.94
H	23.69	15.18	10.53	7.99	10.86	4.70
I	56.47	17.92	13.33	8.23	12.72	5.66
Total ETo[1]	32.17					
Total Rain[2]	11.99					
Total ETc[3]	25.74	19.30	19.30	16.09	16.09	9.65
TexasET Recommendation	18.32	9.65	6.77	4.51	6.55	2.50

[1] Total ETo calculated using the standardized Penmen-Monteith method using weather data collected at the Texas A&M University Golf Course, College Station, Texas.
[2] Total Rainfall collected from TexasET Network Weather Station “TAMU Golf Course”
[3] Rainfall and Adjustment Factor not included in this calculation

Table 10. Fall Performance. Irrigation amount (inches) applied for each controller station. Yellow denotes values within +/- 20 % of TexasET Recommendation. Red indicates values in excess of ETc.

Controller	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	4.80	2.38	1.68	1.92	1.05	0.00
B	4.41	2.80	2.06	1.47	2.24	0.00
C	3.64	1.53	0.71	0.97	0.59	0.00
D	13.01	8.42	6.56	4.17	5.61	2.72
E	4.26	2.31	1.10	0.25	0.79	0.00
F	3.82	5.84	4.90	1.74	2.78	1.79
G	3.99	2.49	1.86	1.16	1.81	0.79
H	4.20	2.69	1.87	1.42	1.93	0.83
I	3.83	2.50	1.71	1.08	0.95	0.72
Total ETo[1]	7.43					
Total Rain[2]	4.42					
Total ETc[3]	5.94	4.46	4.46	3.72	3.72	2.23
TexasET Recommendations	3.35	1.51	1.07	0.75	1.04	0.44

[1] Total ETo calculated using the standardized Penmen-Monteith method using weather data collected at the Texas A&M University Golf Course, College Station, Texas.
[2] Total Rainfall collected from TexasET Network Weather Station “TAMU Golf Course”
[3] Rainfall and Adjustment Factor not included in this calculation

Table 11. Irrigation adequacy during the entire testing period (April 30-December 2, 2012)

Controller	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
B	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
C	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
D	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive
E	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
F	Adequate	Excessive	Excessive	Adequate	Adequate	Adequate
G	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
H	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
I	Excessive	Adequate	Adequate	Adequate	Adequate	Adequate

Table 12. Irrigation adequacy during the Summer (April 30-September 30, 2012)

Controller	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
B	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
C	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
D	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive
E	Excessive	Adequate	Adequate	Adequate	Adequate	Adequate
F	Adequate	Adequate	Excessive	Adequate	Adequate	Adequate
G	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
H	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
I	Excessive	Adequate	Adequate	Adequate	Adequate	Adequate

Table 13. Irrigation adequacy during the Fall (October 1-December 2, 2012)

Controller	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6
A	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
B	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
C	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
D	Excessive	Excessive	Excessive	Excessive	Excessive	Excessive
E	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
F	Adequate	Excessive	Excessive	Adequate	Adequate	Adequate
G	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
H	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate
I	Adequate	Adequate	Adequate	Adequate	Adequate	Adequate

DISCUSSION AND CONCLUSIONS

Over the past four years since starting our "end-user" evaluation of smart controllers, we have seen improvement in their performance. However, the communication and software failures that were evident in our field surveys conducted in San Antonio in 2006 (Fipps, 2008) continue to be a problem for some controllers. In the past four years of bench testing, we have seen some reduction in excessive irrigation characteristics of controllers.

Our emphasis continues to be an "end-user" evaluation, how controllers preform as installed in the field. The "end-user" is defined as the landscape or irrigation contractor (such as a licensed irrigator in Texas) who installs and programs the controller.

Although the general performance of the controllers has gradually increased over the last four years, we continue to observe controllers irrigating in excess of ETc. Since ETc is defined as the ETo x Kc, it is the largest possible amount of water a plant will need if no rainfall occurs. This year, one controller consistently irrigated in excess of ETc, even though16.41 inches of rainfall occurred during the study. The causes of such excessive irrigation volumes are likely due to improper ETo values and/or insufficient accounting for rainfall.

Three (3) controllers were equipped with tipping-bucket rain gauges which measure actual rainfall and six (6) controllers were equipped with rainfall shutoff sensors as required by Texas landscape irrigation regulations. Rainfall shutoff sensors detect the presence of rainfall and interrupt the irrigation event. During the 2012 evaluation period, below average rainfall occurred. The summer period had the most rainfall (11.99 inches), and no major differences in performance observed between controllers using rain gauges and those using rainfall shutoff devices. This is in contrast to the 2010 study during which over 17 inches of rainfall occurred; and controllers using rain gauges applied irrigation amounts much closer to the recommendations of TexasET.

For a controller to pass our test, it would need to meet plant water requirements (TexasET Recommendations) for all six stations. Of the nine (9) controllers tested, none successfully passed the test during both summer and fall seasons. However, one controller passed for the summer irrigation season. Results over the last four (4) years have consistently shown that some of the controllers over-irrigate (i.e., apply more water than is reasonably needed). This year, due to the amount of rainfall received during the study, no controller applied an inadequate amount of water compared to 2011 when six (6) controllers failed to meet minimum plant water requirements.

Generally, there was no difference in performance between controllers with on-site sensors and those controllers which have ET sent to the controller. Previous years evaluations had shown those controllers with on-site sensors to irrigate much closer to the recommendations of the TexasET Network.

Current plans are to continue evaluation of controllers into the 2013 year. While water savings shows promise through the use of some smart irrigation controllers, excessive irrigation is still occurring under some landscape scenarios. Continued evaluation and work with the manufacturers is needed to fine tune these controllers even more to achieve as much water savings as possible.

Appendix

Appendix A

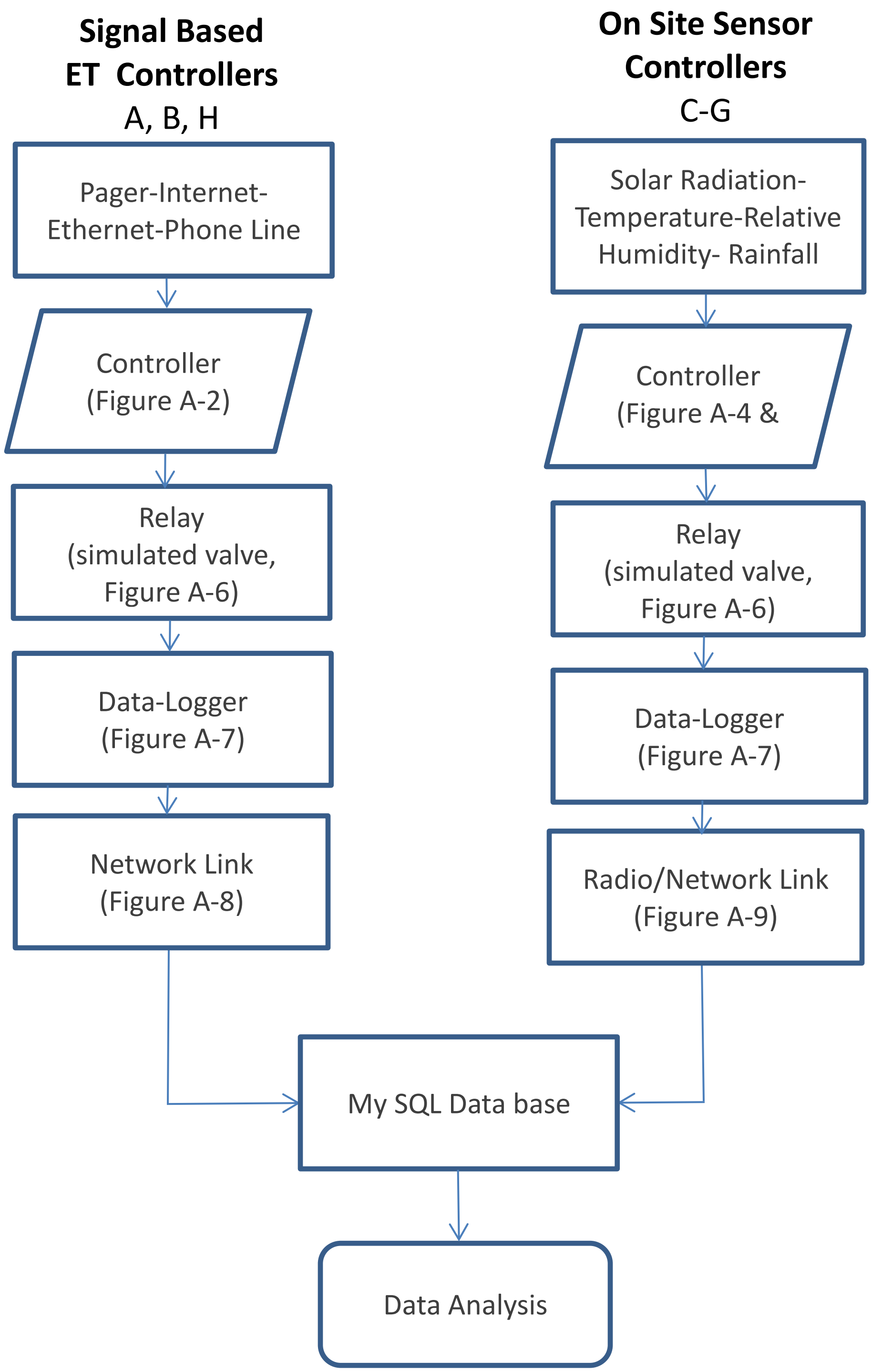

Figure A-1. System Set-Up and Data Flow

Appendix B

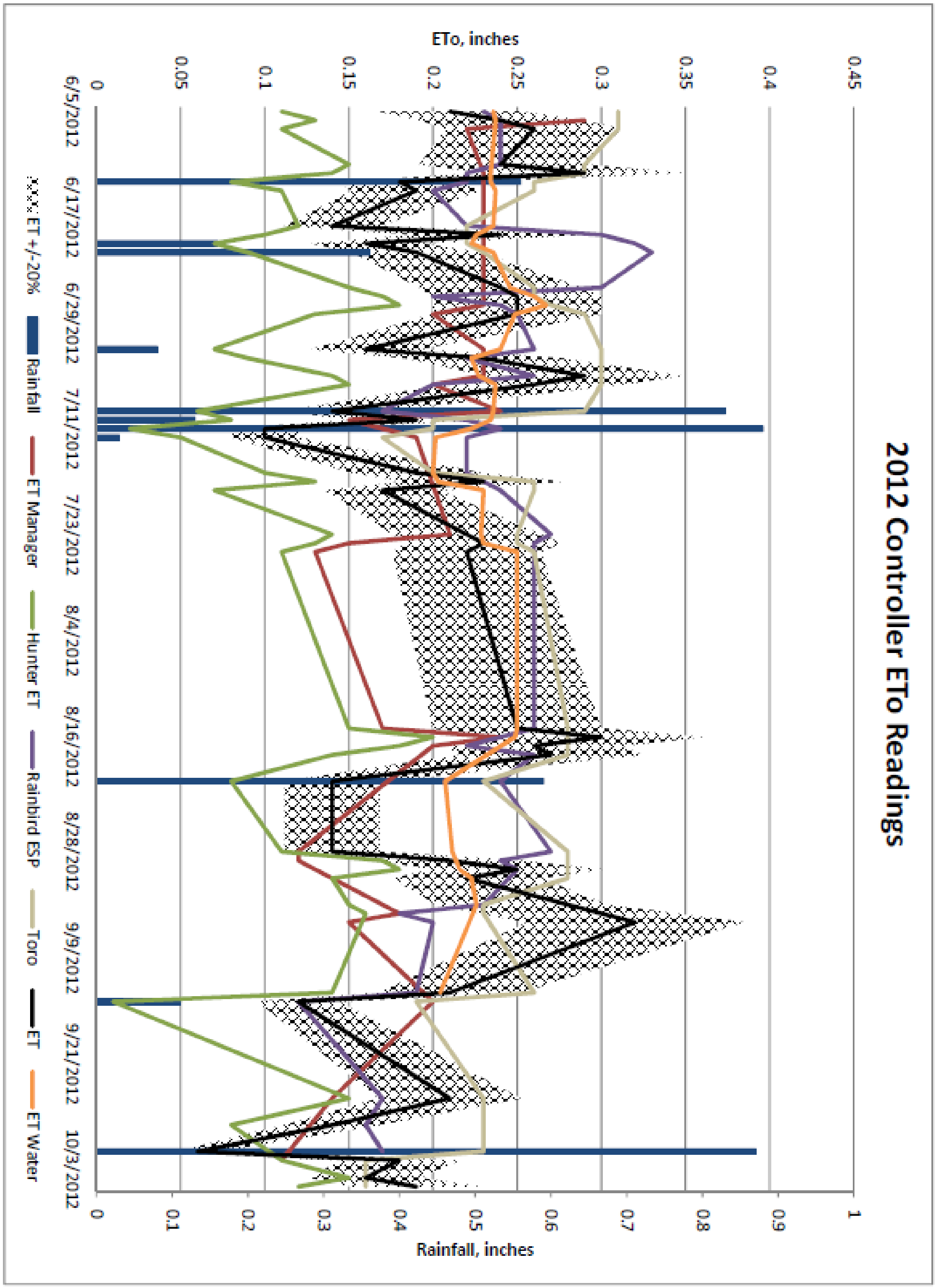

Figure B-1

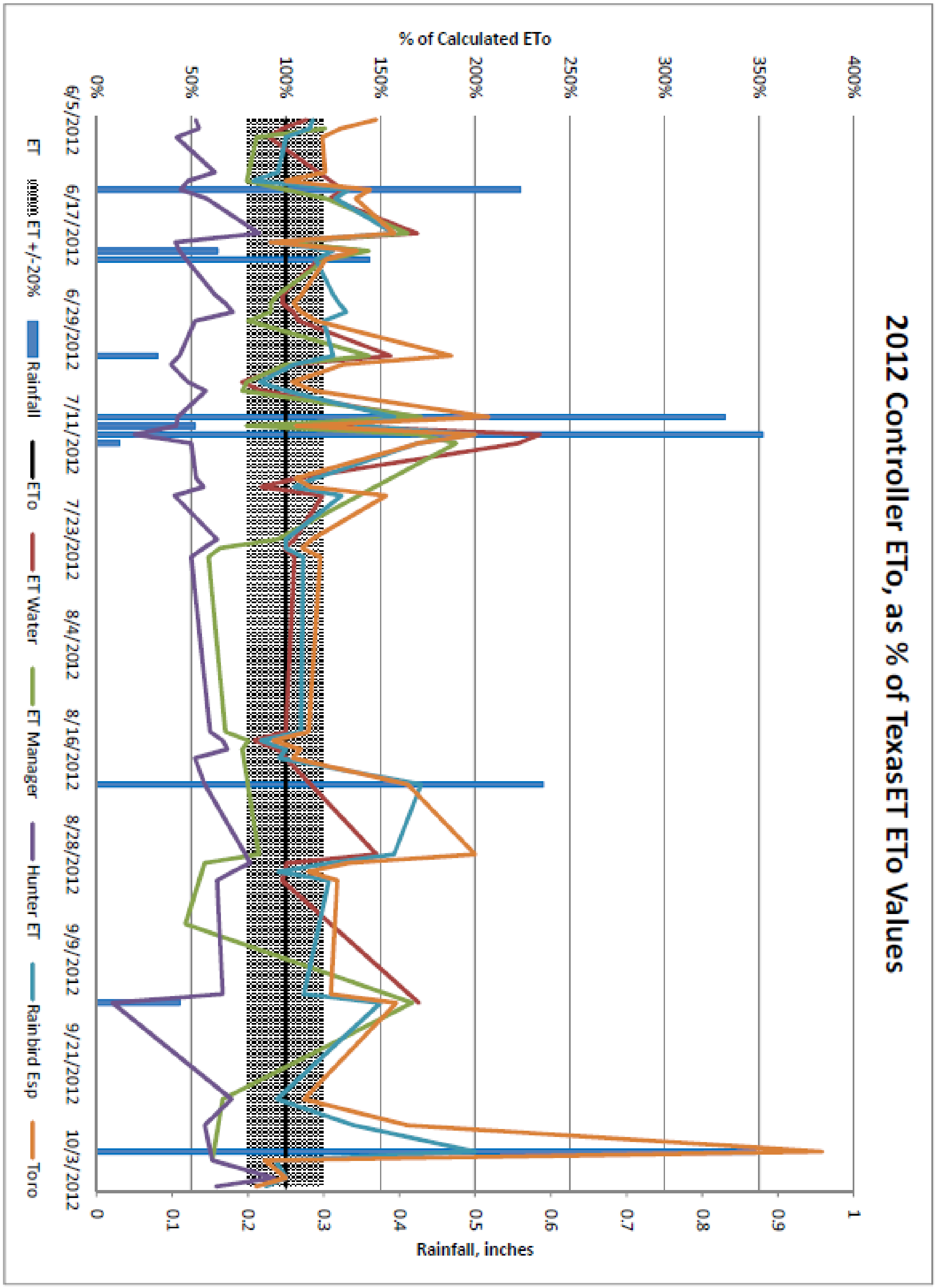
2012 Controller ETo, as % of TexasET ETo Values
% of Calculated ETo
0%
50%
100%
150%
200%
250%
300%
350%
400%
6/5/2012
6/17/2012
6/29/2012
7/11/2012
7/23/2012
8/4/2012
8/16/2012
8/28/2012
9/9/2012
9/21/2012
10/3/2012
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Rainfall, inches
ET
ET +/-20%
Rainfall
ETo
ET Water
ET Manager
Hunter ET
Rainbird Esp
Toro

Figure B-2

References

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Remote Telemetry:
Innovative Solutions for Managing Remote Irrigation Sites

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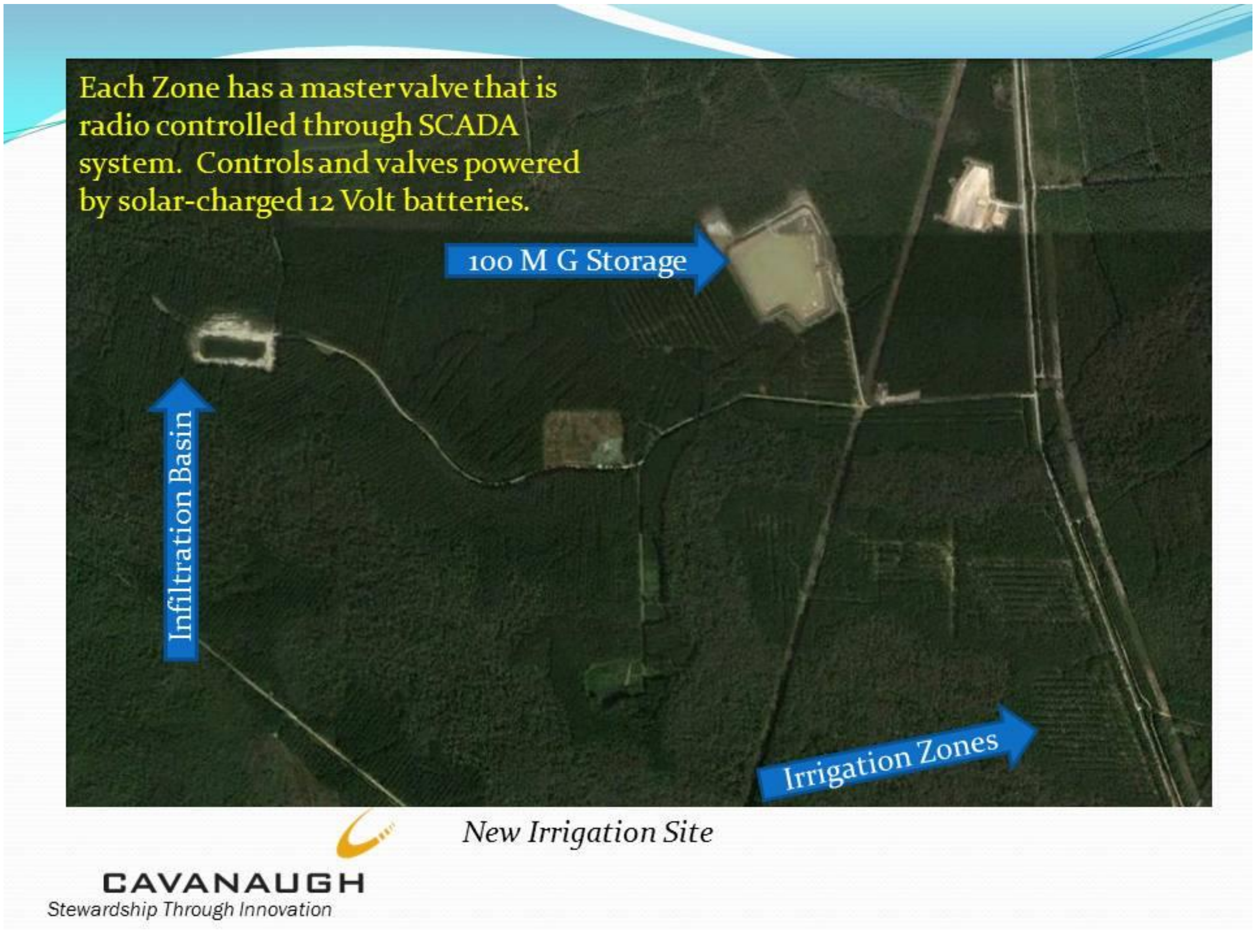
Abstract - *In 2006, the Town of Surf City, an island town located in Coastal North Carolina, began the process of expanding their wastewater facilities to meet the demands of a growing population and increasing seasonal tourism. The Town's treated wastewater is designed and permitted to meet North Carolina Reclaimed Water standards. The Town owns and operates an 88-acre sprayfield that uses small impact sprinklers to irrigate a grass receiving crop. The existing fields operate at maximum capacity, which is less than half of the Town's 10-year flow projection capacity needs. This existing sprayfield site is also bound on all sides by properties that are either unusable or unattainable by the Town for use in expansion of the non-discharge irrigation system. After an extensive search for available and usable property, the Town acquired a 2,200-acre tract under managed pine that would serve the Town's long-term needs. However, this tract of land is eight miles from the Town's wastewater facilities, in a remote, rural area. This paper describes the challenges presented in managing this remote site that has limited access and coverage by conventional telecommunications infrastructure, and the strategies implemented to overcome these challenges; including solar-powered radio controls system and custom-designed irrigation management system.*

Keywords: Solar-powered radio control systems, remote system management strategies, remote effluent utilization sites, integration of SCADA system in a remote utilization sites



Background

The beaches of coastal North Carolina have become increasingly popular, and the expanding tourism season exponentially increases the demand on wastewater facilities during the summer months. Environmental regulations and water stewardship goals require many of these areas, such as the Town of Surf City, located in coastal Pender County North Carolina, to utilize non-discharge systems for wastewater disposal. By far, the most popular form of non-discharge disposal employed by these systems is through the use of irrigation – either as a dedicated site for disposal, or through some beneficial reuse of the treated wastewater effluent ("reclaimed water") to offset an existing or proposed demand on fresh water supplies.

There were many challenges facing the Town of Surf City as they looked to expand their non-discharge wastewater system, which also required expansion of the dedicated irrigation sites (spray fields) and development of reclaimed water reuse strategies. A primary challenge was that the wastewater facilities serve a permanent population of about 2,000 people; but this served population increases to more than 20,000 in the summer as tourists and seasonal occupants arrive to spend the warm season at the beach. This vast increase in population correlates to a substantial seasonal increase in wastewater treated, which ultimately means a seasonal increase in the amount of water to be irrigated. The original 0.6 MGD wastewater plant was a simple lagoon based system circa 1990 with a spray irrigation system comprised of approximately 88 acres of small-bore impact sprinklers irrigating a Bermuda grass receiving crop. Another challenge associated with the expansion plans was that the existing wastewater plant and sprayfield were 'land locked,' or bound on all sides by properties that are either unusable or unattainable by the Town for use in expansion of the non-discharge irrigation system. Consequentially, this meant that the Town must look to acquire additional land away from the existing facilities and control system.

As you might imagine, land in this area has, historically, been actively sought for commercial and residential development to meet the increasing demands of more and more people moving to and visiting the area. Being in coastal, eastern North Carolina, the sizes of parcels of land are relatively small, and wetland areas are prevalent. Based on the foreseeable wastewater needs of the Town, it was initially determined that the Town would need to increase its wastewater system, and thus its irrigation system, five-fold (to 3.0 MGD). The existing irrigation site, as previously mentioned, is approximately 88 acres of sandy, coastal soils. Given the expansion needs, the Town began looking for a parcel, or parcels, of land that could support roughly 440 acres of irrigation – assuming similar sandy soils. It quickly became evident that none of the adjacent properties, or properties within the immediate area of the existing system, would be capable of being conjoined to satisfy this requirement.

Finally, the propensity for management problems caused by inclement weather was noted as a critical challenge for the Town. The existing system had only six days of storage capacity, which put the Town and the Operator in a very precarious situation during periods of wet weather. During the 1990's, several named storms and hurricanes dumped inches of water on the area, which resulted in localized flooding. Some of the flooded areas, unfortunately, resulted in surcharging the sewer system and creating an increased volume of treated effluent to be managed by the irrigation system; not to mention the volume of rainfall captured by the storage ponds and the wetness the rainfall created in the irrigation fields. The existing storage and irrigation system had no remote monitoring or controls system, which meant that the system had to be manned to be monitored. This is problematic not only during inclement weather, but often in the days that follow as flooding and felled trees often inhibit transportation in the area.

Given these considerations, plans were developed to expand the Town's existing wastewater treatment and irrigation system to a first phase of 1.5 MGD utilizing a sequencing batch reactor (SBR) capable of producing reclaimed water quality effluent. The Town sought to: acquire a sizable tract of land to utilize as a dedicated irrigation site – even though this required looking at parcels of land several miles away, promote the reuse of water for future customers, and implement a monitoring and controls system that provided the Operators with the ability to manage the system from a safe location during inclement weather. Cavanaugh & Associates, P.A. helped the Town of Surf City identify and acquire a 2,200 acre tract of forested land about eight miles from the Town's wastewater facilities, to serve as the irrigation site and to provide additional storage. The following describes the remote monitoring and control system developed for the Town, and the ways in which it aids in overcoming the challenges described above.

Remote Communication is the Key

It was important at the onset of the expansion planning to evaluate the current means of remote monitoring and controls utilized by the Town for other critical infrastructure and essential operations. The Town had already gone through an extensive evaluation of the challenges and benefits of differing types of remote monitoring and controls systems for other infrastructure systems, such as the Town's water distribution system and the sewer collection system. Given the likelihood of power outages and disruptions in telecommunication services, the Town quickly moved away from relying on hard-wire control systems that require conventional telephone service. The decision was reinforced to utilize a system that combined the use of internal radio communications, managed by the Town, and the internet.

The existing VHF radio communications system utilized by the Town consisted of a primary communications tower at the Town's drinking water plant, with repeaters distributed around the Town to provide signal strength. The existing drinking water distribution system and much of the sewer collection system was already connected to this supervisory control and data acquisition ("SCADA") system. The addition of the monitoring and controls of the wastewater treatment plant made perfect sense, and provided the Operators the ability to monitor and control all of this infrastructure from either the drinking water plan or the wastewater plant, providing redundancy of data and the opportunity for the Operators to control the system from either location should inclement weather prevent access to one of the sites.

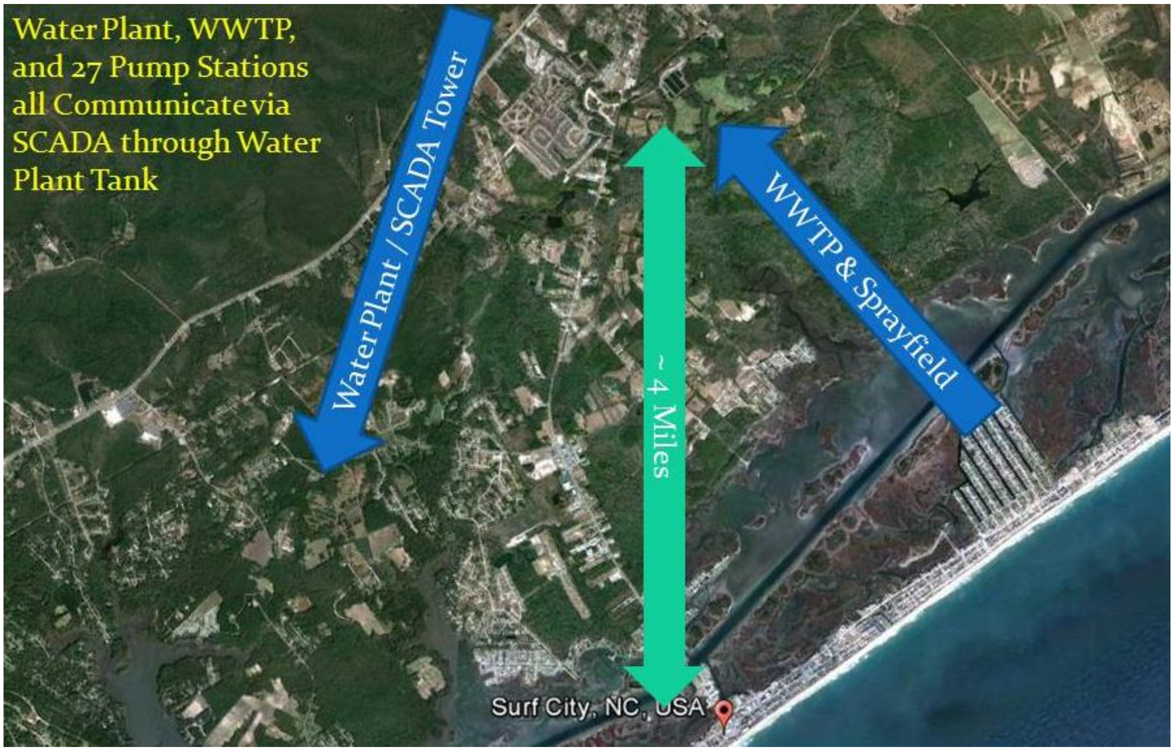


Figure 1. Existing SCADA Communications System Map

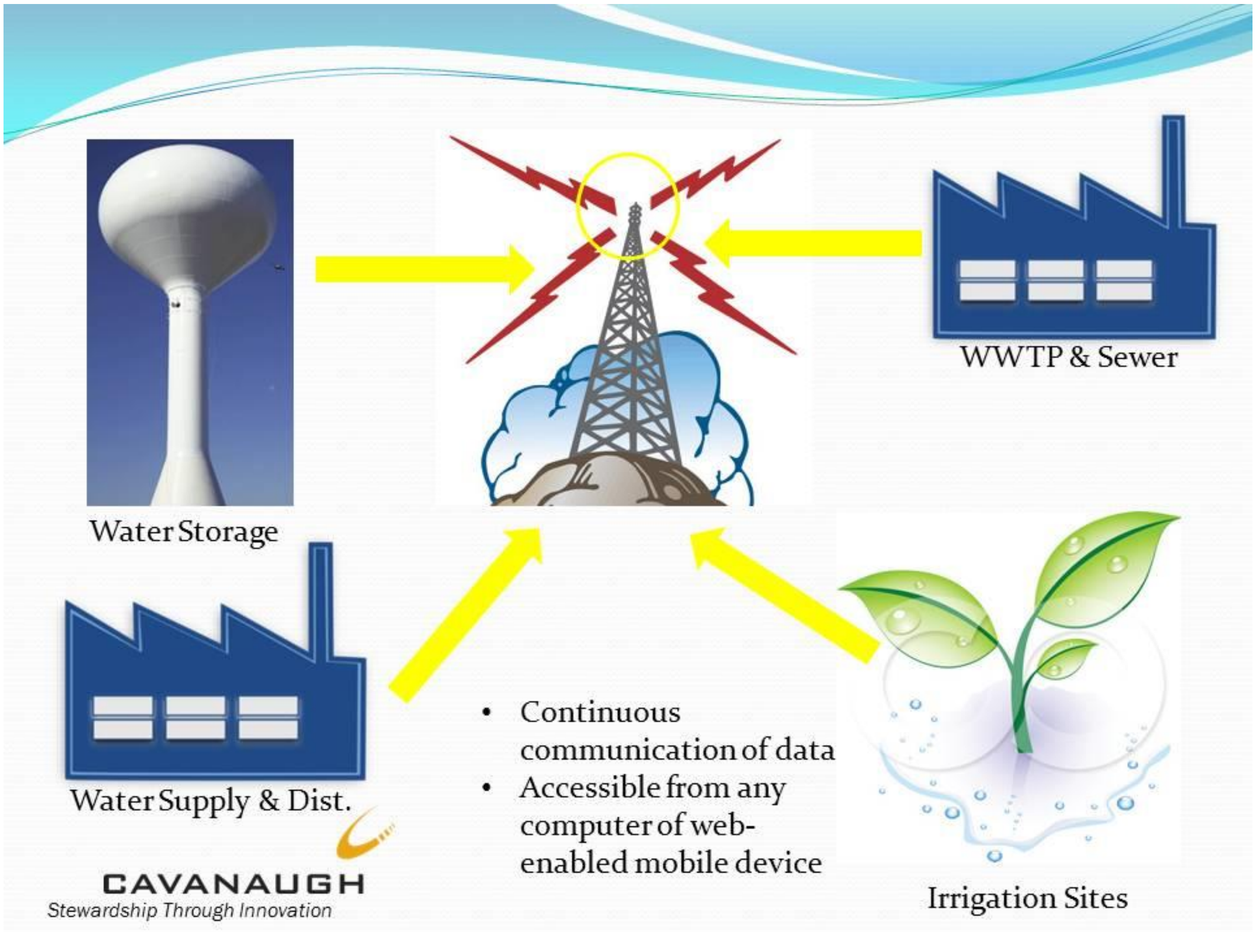


Figure 2. Town SCADA System Communications Schematic

The parcel of property acquired for the expansion of the irrigation system was over 8.5 miles away from the existing wastewater plant, and over 12 miles away from the centralized communications tower. This distance required upgrading the strength of the broadcast signal, and a decision was made to place a second broadcast antenna at the existing wastewater plant. Again, this provided redundancy for the critical operations of the Town's infrastructure, should one of the communications towers be damaged by excessive winds or flying debris.

Although the Town's operational philosophy included staffing the irrigation site during normal irrigation events to monitor for problems and errata, the ability to remotely control the site in case of emergencies, and monitor the operations of an expansive, wooded, and remote site were of utmost importance. The remote nature of the site resulted in poor cellular phone reception and inadequate unreliable phone line communications. Moreover, the area was well known and documented to suffer from multiple nearby lightning strikes annually, which can wreak havoc on wired control systems. With these factors in mind, the decision to continue the use of VHF radio communications, augmented with the ability to communicate to the Town's SCADA system via any computer connected to a secure network over the internet was clear.

Figure 3. Expansion of SCADA Communications System for New Irrigation Site

Figure 4. Communications Tower Installed at Remote Site

Access to Meaningful Data

The opportunity also existed to integrate the irrigation operations with the Town's existing SCADA system to provide the operators with a much more informative and complete set of data regarding the Town's water cycle. Rather than purchasing an off-the-shelf irrigation control system, the Town decided to build in the control functionality and monitoring typically provided through commercial irrigation control applications into their existing SCADA program. Using the existing SCADA software for irrigation program control afforded several advantages:

- The software used by the Town is an 'open source' application; meaning future additions and modifications to the programs could be accomplished by any of a large number of SCADA system integrators and programmers. This allowed the Town with the greatest flexibility in managing the costs and customer service experience.
- As technology improves over time (new sensors, meters, gauges, etc.), these devices can be added without purchasing an upgrade or entire new software module.
- The "irrigation controls software" would be tied to the other pertinent data available for managing the water cycle of the system, including:
    - Drinking water supply consumption
    - Available storage capacity
    - Influent flow at waste water plant (compared to drinking water flow, points to consumption as well as inflow, infiltration, or unmetered source flows)
    - Weather data (temperature, precipitation, humidity, etc.)
    - Sewer collection system status (pump status, equipment failures that impact effluent quality, etc.)
    - Wastewater plant data (pump status, equipment failures that impact effluent quality, real-time constituent monitoring such as disinfection system efficacy, etc.)

Not only would the operators receive information about storage capacity and application events of the irrigation system, but also receive information about rainfall across the Town, tidal influx, and water usage. Flow meters on all major pump stations also provide the operators with information regarding the influent flow patterns and predictions on flow to the wastewater storage system over a short period of time. Wastewater plant data can provide the operator with real-time and current data on the effluent constituents, including nutrient concentrations and pathogen information. All of this information allows the operators to develop long-term trends for daily and seasonal flows to the irrigation system for more accurate and predictable irrigation budgeting, as well as better manage the performance of the irrigation system and safety of the workers. Total integration with SCADA allows the operator to control the entire water resources system.

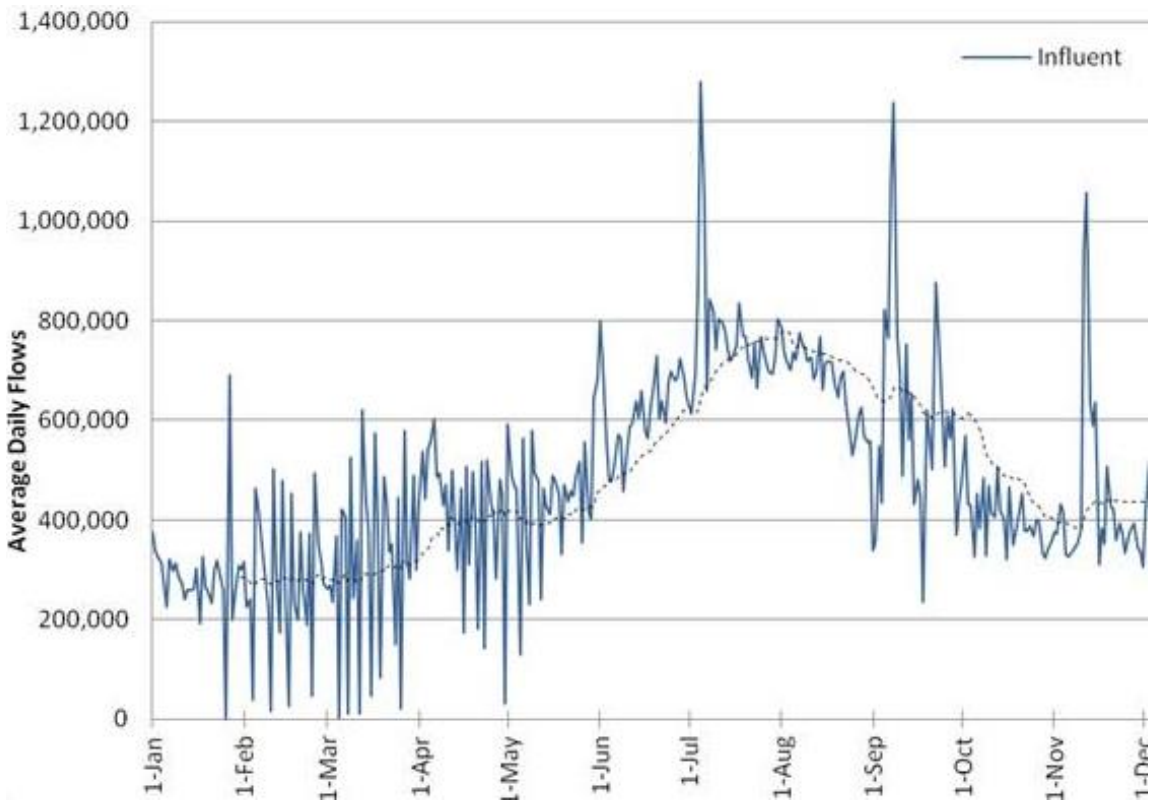


Figure 5. Example Influent Flow Trend Graph from SCADA System

Irrigation Control System for Remote Site

The remote irrigation control system is comprised not only of a wireless connection to the primary control facilities, but also a wireless zone control system to further overcome the challenges discussed above associated with typical hard-wired zone control systems. A combination of manual zone valves and automated zone valves were installed to control the sprinklers, which communicate to the centralized server at the irrigation pump station. Each zone has a master diaphragm valve that is actuated by a small, electric solenoid valve. The solenoid valves operate on DC current supplied by 12-volt deep cell batteries located in the zone control panels at each zone. The solenoid valves are controlled by a small programmable logic controller (PLC) in each zone control panel, also powered by the 12-volt batteries. When the SCADA system sends a signal for any zone control valve to open, the solenoid valve opens creating a pressure differential on the diaphragm (irrigation system must be pressurized by irrigation pumps for pressure differential to be created). This pressure differential operates the diaphragm, thus opening and closing the valves, as desired. Using this configuration, a simple, inexpensive ¼” solenoid valve is able to open and close 8” to 18” zone control valves.

The 12-volt batteries powering the zone control panel and solenoid valves are connected to solar panels mounted on the communications tower at each zone. The solar panels were sized to provide sufficient charging capabilities to maintain functional power for a 5-day period; ensuring "cloudy days" do not limit the functionality of the system. Power efficiency is further managed by having the PLC "sleep" a majority of the time, which consumes far less power than staying "on" continuously. The PLC "wakes up" for 30 seconds every 5 minutes to listen for a control signal. In this fashion, the PLC is only fully powered approximately 10% of the time.

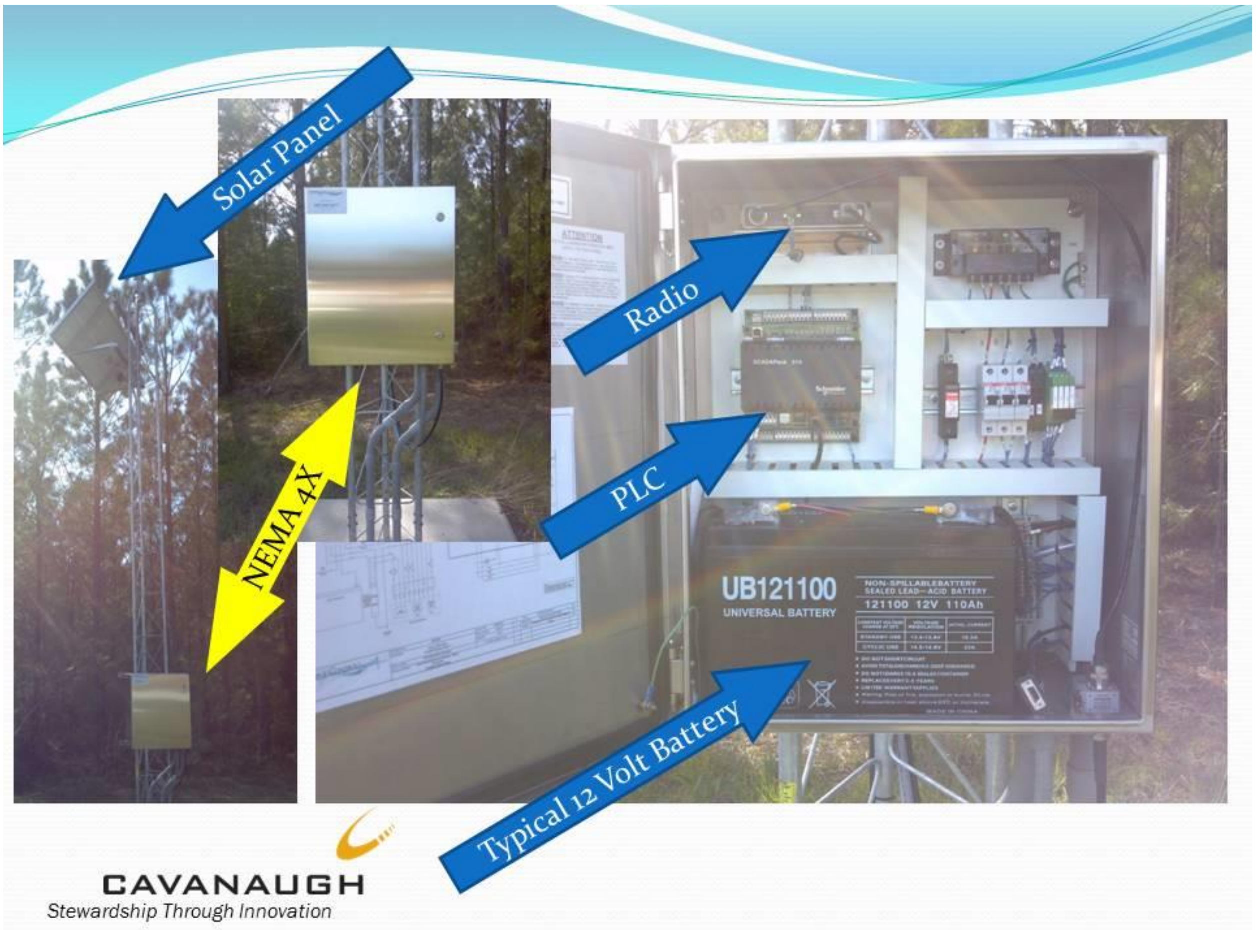


Figure 6. Typical Remote Irrigation Control System Installation

There are two main control valves that direct effluent flow to either of two available storage basins to provide the operator with maximum flexibility. It was determined to keep these two valves in continuous operation to provide the operator instant control over flow direction (flow direction was considered to be a critical function requiring "instantaneous" changes in the event of system malfunction to prevent spills or create safe conditions). As such, multiple 12-volt batteries were provided for these control panels, and larger solar panels provided.

The SCADA system, also serving as the irrigation program control package, controls the frequency and duration of each irrigation event for each zone. The SCADA software was developed to include 48 customizable programs (expandable to a near infinite number of programs) that allow for multiple irrigation events of zones within a single program. This flexibility of programming allows the operator to perform multiple zone doses during a single program to provide specific dosing of each irrigation zone. There are 32 valve calls per program, and no set pattern. The irrigation pumps are controlled by variable frequency drives (VFD's) that allow for pump speed control. Pumps ramp up when each program is initiated to provide system pressure for control valve manipulation, and ramp down between programs to prevent over pressurization and water hammer as valves close. Each irrigation zone has an adjustable pressure set point, and the VFD-driven pumps adjust speed during irrigation events to maintain desired zone pressure. Additional, programmable safeguards were added to allow the operator to program alarm conditions for pressure and flow. For example, if zone flow (at the pressure set point) exceeds a set percentage (1-100%), the pumps shut down. This is an important monitoring feature of the system to indicate to the Operator that a sprinkler riser may be broken or that a supply line may be broken. Automatic pump shut-down for this alarm condition minimizes, and virtually eliminates, runoff due to breakage. If this were a case of clean water irrigation rather than treated wastewater effluent, the same capability will prevent unnecessary water waste; or nutrient/pesticide waste in the case of fertigation. Similarly, low- and high-pressure alarm set points may indicate valve failure, and similarly result in pump shut-down. All of these set-points are adjustable by the Operator, affording flexibility as the system changes or expands over time.

Conclusions

Implementation of remote irrigation management systems, as described for this project, provides real-time data and control of critical irrigation infrastructure by the Operators. Further integration of total water cycle data, such as source flows, weather data, and storage availability provide for better irrigation scheduling, water budgeting, and decision making. This data may also be used by the Operators to better predict storage needs, application rates, and other operational considerations as time moves forward and more data is kept for trend analysis. Integrating irrigation management software applications with other existing supervisory control and data acquisition (SCADA) system applications affords the Operators and system owners with the greatest amount of control and flexibility – able to not only shut-off critical irrigation system components in case of emergency or inclement weather, but also by managing (even shutting down) source flow contributors, such as upstream pump stations. The ability to remotely control critical pumps and valves by both internal VHF radio system and by internet-capable devices provides the Operators, in this case, a means of monitoring and controlling the system from safe locations in the event of inclement weather, such as hurricanes. This ability will enable the Operators to control and manipulate storage and flows, preventing spills and overflows from the wastewater system.

The use of radio control systems affords the opportunity to avoid the expense and challenges associated with the installation and operation of typical hardwire control systems. Using battery-powered zone control systems and zone control valves, recharged by solar panels, also eliminates the hazards of installing electrical lines in a wet service location, and the expense of installing miles of high-voltage power lines. Installations, such as the remote irrigation control system employed by the Town of Surf City, demonstrate the improved management techniques that continue to be availed to irrigation system operators as radio communications, internet-enabled mobile devices, and solar-powered control systems become more affordable and accessible.

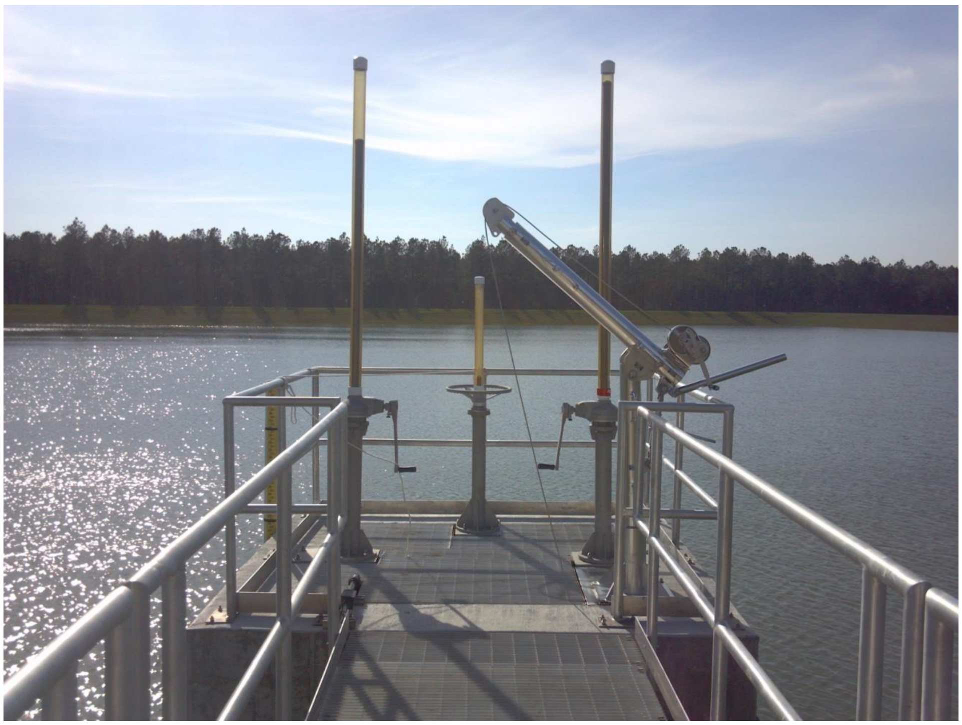


Figure 7. Inlet Control Structure at 32-acre Storage Pond Serving Surf City Irrigation System

About the Author:

William G. "Gus" Simmons, Jr., P.E. served as Engineer in Responsible Charge and Lead Designer for the Town of Surf City Irrigation System Expansion. Gus has designed and operated thousands of acres of sprinkler irrigation for the purposes of wastewater effluent utilization and beneficial reuse for agricultural, industrial, and municipal installations across the United States. Gus continues to work with the Town of Surf City and the irrigation system Operators in analyzing the data associated with the Town's total water balance, and planning for efficient use and expansion of the Town's irrigation system infrastructure. For more information, please visit **www.cavanaughsolutions.com**.

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